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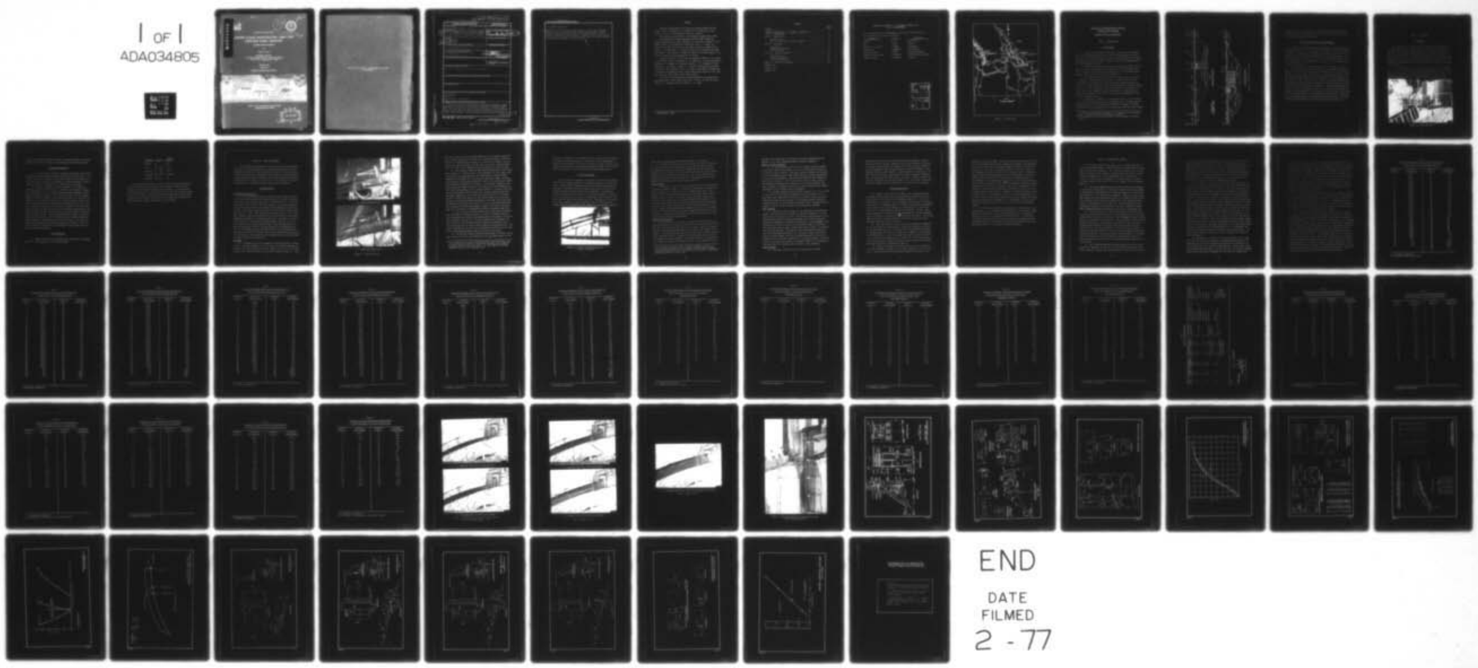

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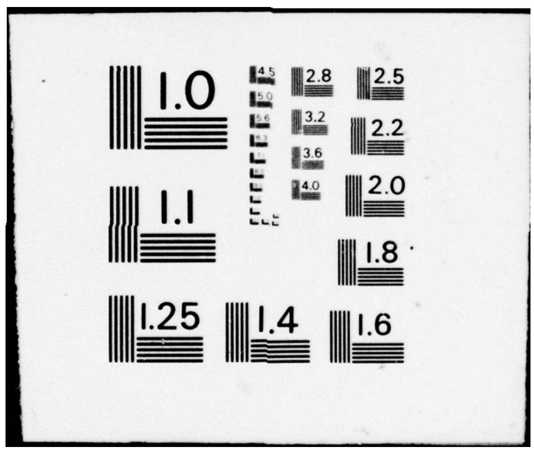
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TECHNICAL REPORT H-76-21

# CENTER SLUICE INVESTIGATION, LIBBY DAM KOOTENAI RIVER, MONTANA

## Hydraulic Model Investigation

by

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Final Report

Approved For Public Release; Distribution Unlimited

Prepared for U. S. Army Engineer District, Seattle
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The model study of the center sluice, Libby Dam, was conducted to determine the causes of and to develop means for preventing the cavitation damage experienced in the sluices. The study was conducted in a 1:20-scale model of the center sluice which reproduced the "as-built" geometry of the bell-mouthed intake, emergency gate slot, regulating gate and gate well, and parabolic trajectory of the sluiceway. The model helped to define undesirable hydraulic


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20. ABSTRACT (Continued).

conditions that have caused cavitation damage in the prototype structure. Through the use of the model, an aeration device was developed to ventilate the jet and prevent cavitation damage. The recommended aerator (type 7) provided a high degree of aeration without adversely altering flow conditions in the sluice. A certain roof modification was suggested to prevent unstable flow and cavitation damage in the sluice intake.

# PREFACE

The model investigation reported herein was authorized by the Office, Chief of Engineers, U. S. Army, on 18 October 1974, at the request of the U. S. Army Engineer District, Seattle.

The studies were conducted in the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) during the period December 1974 to March 1976 under the direction of Messrs. H. B. Simmons, Chief of the Hydraulics Laboratory, and J. L. Grace, Jr., Chief of the Structures Division, and under the direct supervision of Messrs. J. P. Bohan and N. R. Oswalt, Chiefs of the Spillways and Channels Branch. The engineer in immediate charge of the model was Mr. M. S. Dortch. This report was prepared by Mr. Dortch.

During the course of the model investigation, Messrs. S. B. Powell of the Office, Chief of Engineers, H. A. Smith, Jr., of the North Pacific Division, R. P. Regan of the Seattle District, T. E. Murphy* of Vicksburg, Miss. (previously of WES), J. W. Ball* of Colorado State University, and D. M. Colgate* of the U. S. Bureau of Reclamation visited WES to observe model demonstrations, review and discuss results of the tests, and correlate these results with design studies.

Directors of WES during the testing program and the preparation and publication of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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* Consultants to NPS.

CONTENTS

## CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| inches | 25.4 | millimetres |
| feet | 0.3048 | metres |
| miles (U. S. statute) | 1.609344 | kilometres |
| square feet | 0.09290304 | square metres |
| feet per second | 0.3048 | metres per second |
| cubic feet per second | 0.02831685 | cubic metres per second |
| degrees (angle) | 0.01745329 | radians |

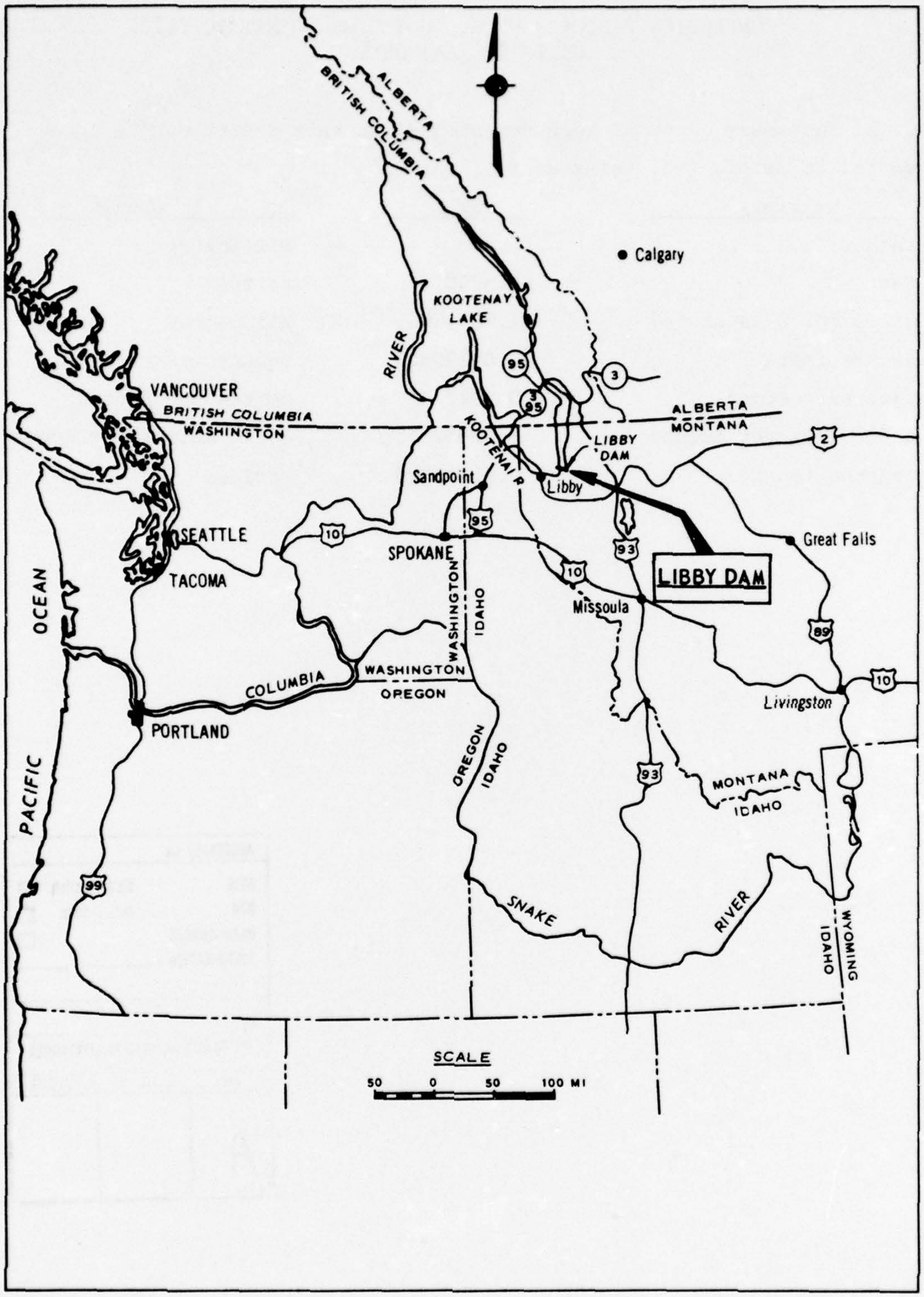


Figure 1. Location map

CENTER SLUICE INVESTIGATION, LIBBY DAM

KOOTENAI RIVER, MONTANA

Hydraulic Model Investigation

# PART I: INTRODUCTION

## The Prototype

1. Libby Dam forms Lake Koocanusa and is located on the Kootenai River in northwestern Montana about 219 river miles upstream from the confluence of the Kootenai and the Columbia Rivers, about 17 river miles upstream from the town of Libby, Montana, and 48 miles* downstream from the Canadian border (Figure 1).

2. Libby Dam is a concrete gravity-type dam and contains a spillway section controlled by two tainter gates, three tainter-valved conduits (sluices), and a power plant consisting of four generating units with provisions for four future units (Figure 2).

3. The sluices are used for reservoir storage control. Subject to sufficient inflow volumes, the reservoir is drawn down as low as el 2287** for power production and flood control storage requirements during the low-flow winter and early spring months and refilled to normal full pool (el 2459) during the spring runoff period. The sluices provide flood control capabilities and flexibility for regulating flows during winter drawdown. The location and general configuration of the sluices are shown in Plate 1.

4. Each sluice consists of a bell-mouthed intake, a 17.0-ft-high by 10-ft-wide rectangular conduit, an emergency gate, a tainter gate for regulating flow, and a 22-ft-high by 10-ft-wide rectangular sluiceway extending 240.4 ft downstream from the sluice gate with the invert shaped

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

** All elevations (el) cited herein are in feet referred to mean sea level.

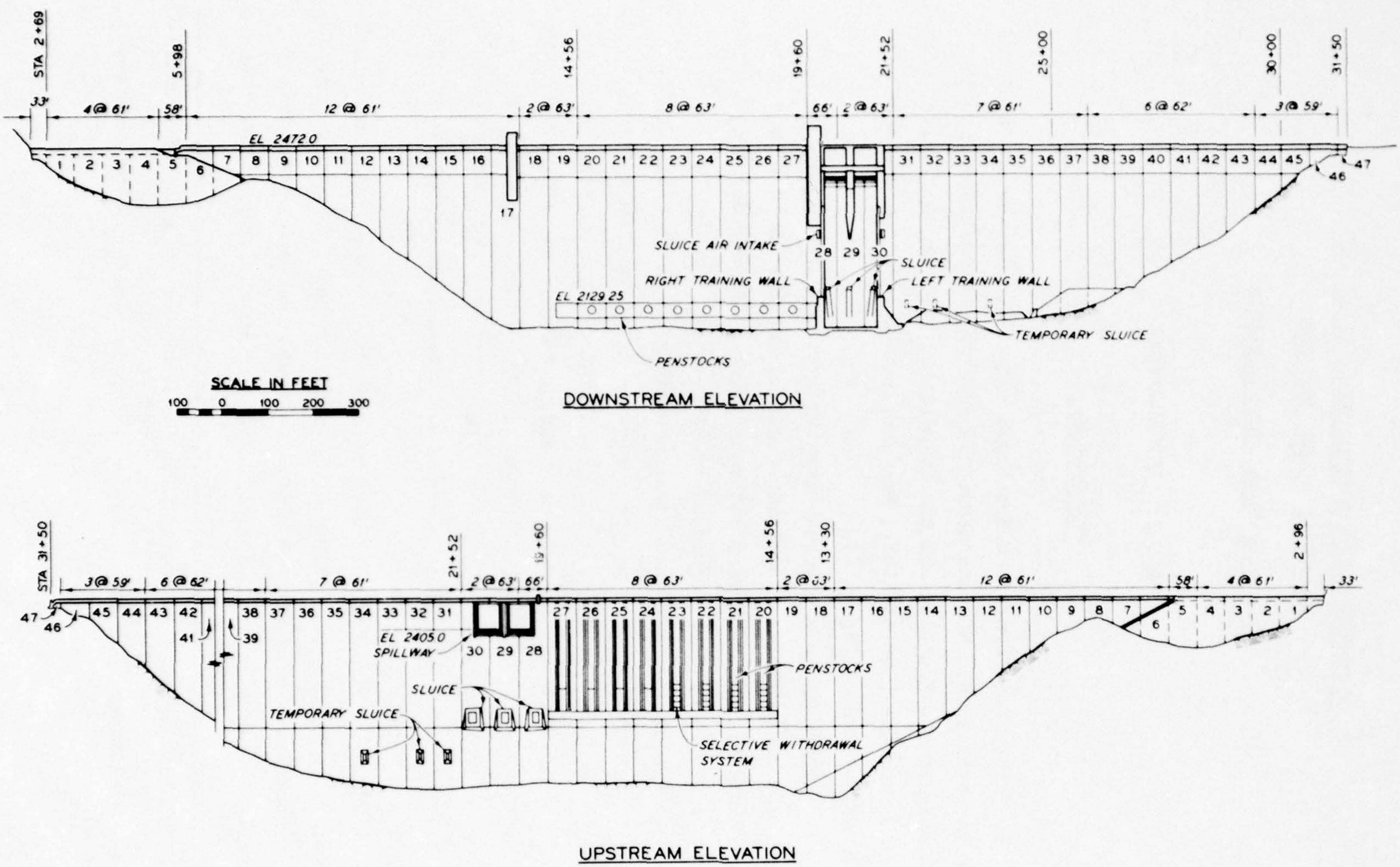



Figure 2. Libby Dam elevations

to the trajectory of a free jet from a head of 265 ft. Each sluice is designed to operate with heads up to 265 ft (pool el 2459) for release of a maximum discharge of 20,000 cfs.

## Need for and Purpose of Model Analysis

5. Massive cavitation damage was discovered in the center sluice following 18 months of operation, and in the right sluice after 28 months of operation. The most severe damage was observed along the invert and sidewalls of the center sluice downstream of the regulating gate. Cavitation damage was also found along the roof of the center sluice immediately upstream of the emergency gate slot and at the downstream face of the emergency gate slot.

6. The purpose of the model study was to determine the causes of and to develop means for preventing the cavitation damage experienced in the sluices. Before the model study was initiated, the solution for preventing cavitation damage along the sluice trajectory was considered by the consultants (see Preface) to be the installation of an aerator in this portion of the sluice. The U. S. Bureau of Reclamation (USBR) has successfully eliminated cavitation damage in spillway tunnels and sluices by aeration of the flow along the boundaries. Testing and evaluation of aeration devices in a hydraulic model of the sluice were considered necessary for the development of an aerator that would satisfactorily aerate all flow boundaries without causing adverse flow conditions. Demonstration of the effectiveness of an aeration device through model tests was certainly advisable before attempting such revisions in the field.

# PART II: THE MODEL

## Description

7. The model of the center sluice (Figure 3) was constructed to an undistorted scale of 1:20 and reproduced the "as-built" geometry of the bell-mouthed intake, emergency gate slot, conduit, sluice gate and gate well, sluiceway with parabolic trajectory, and outlet portal as shown in Plates 2 and 3. The intake, emergency gate slot, conduit, gate well, and sluiceway were fabricated of transparent plastic so that flow conditions could be observed. The sluice (tainter) gate was constructed of sheet metal.

8. A 16-ft-high by 16-ft-diam steel tank was used for a headbay. Water used in the operation of the model was supplied by a recirculating system and discharges were measured by venturi and orifice meters. Pool elevations were measured with a water manometer. Piezometers were

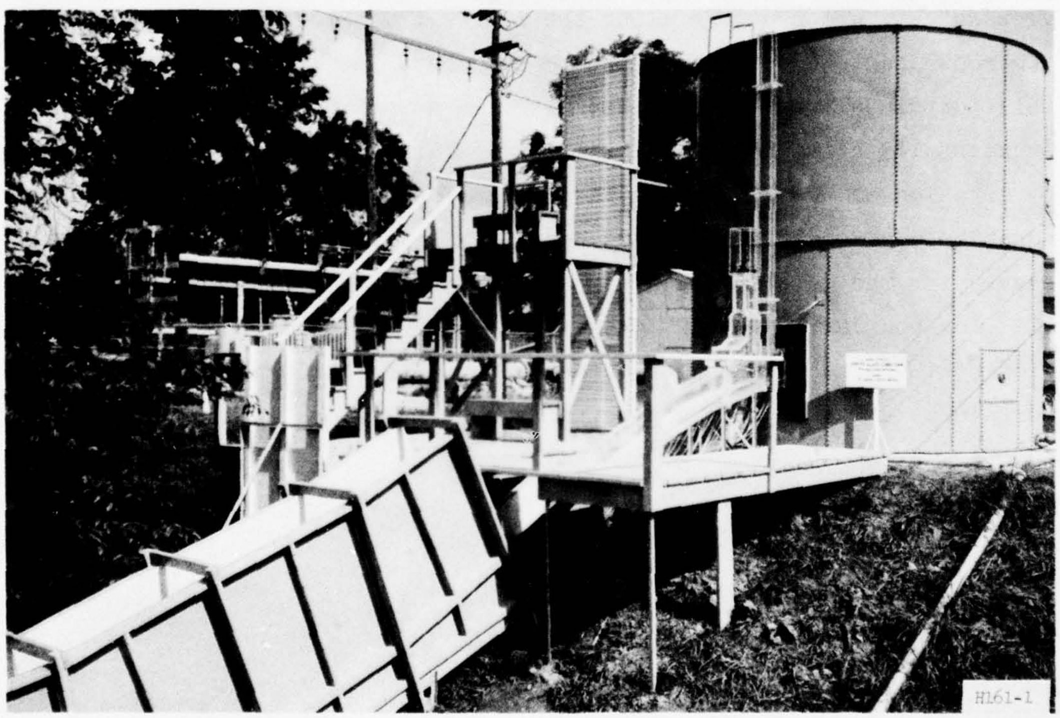



Figure 3. Model facility

installed throughout the model structure to measure pressures. Pressure transducers were used to measure high-frequency pressure fluctuations.

## Design Considerations

9. In the design of the model, geometric similitude was preserved between model and prototype by means of an undistorted scale ratio. The accepted equations of hydraulic similitude, based on the Froudian relation, were used to express the mathematical relations between the dimensional and hydraulic quantities of the model and the prototype.

10. An effort was made to exactly reproduce in the model the parabolic trajectory of the sluice. A survey of the "as-built" trajectory, furnished to the U. S. Army Engineer Waterways Experiment Station (WES) by the Seattle District, was incorporated into the model design. However, it was not possible to mold the model plastic to the exact configuration of the prototype trajectory. Molding the model plastic created a smoother parabolic trajectory than actually exists in the prototype. Definite discontinuities created by construction lift joints are visible in the prototype; and with the velocity heads experienced in the structure (265 ft), such discontinuities could cause negative pressures along the sluice invert. Visual observations and surveys of the prototype show that the lift joint discontinuities are created by small but abrupt changes in trajectory slope at the lift joints. Two lift joint discontinuities were installed along the model trajectory to better reproduce conditions existing in the prototype and to determine the effect of the discontinuities.

## Scale Relations

11. General relations for transfer of the model data to prototype equivalents are presented on the following page:

| Dimension | Ratio | Scale Relation |
| --- | --- | --- |
| Length | $L_r$ | 1:20 |
| Time | $T_r = L_r^{1/2}$ | 1:4.47 |
| Velocity | $V_r = L_r^{1/2}$ | 1:4.47 |
| Discharge | $Q_r = L_r^{5/2}$ | 1:1788.85 |
| Pressure | $P_r = L_r$ | 1:20 |

12. Quantitative transfer of model data to prototype equivalents by the scale relations listed above was considered reliable except for pressures in the cavitation range in the prototype. It is impossible for negative pressures in the prototype to be less than a perfect vacuum, about -34 ft of water. However, in the model, negative pressures indicating prototype pressures less than -34 ft of water are posssible and indicate zones of certain cavitation in the prototype.

## PART III: TESTS AND RESULTS

13. The model study basically consisted of two testing programs. The initial testing program was involved with evaluating the flow and pressure conditions in the existing as-built sluice. The second phase of the study consisted of development and testing of aeration devices to prevent cavitation damage downstream of the sluice gate and evaluation of modifications to the roof of the sluice in the vicinity of the emergency gate slot to improve pressure conditions in this region.

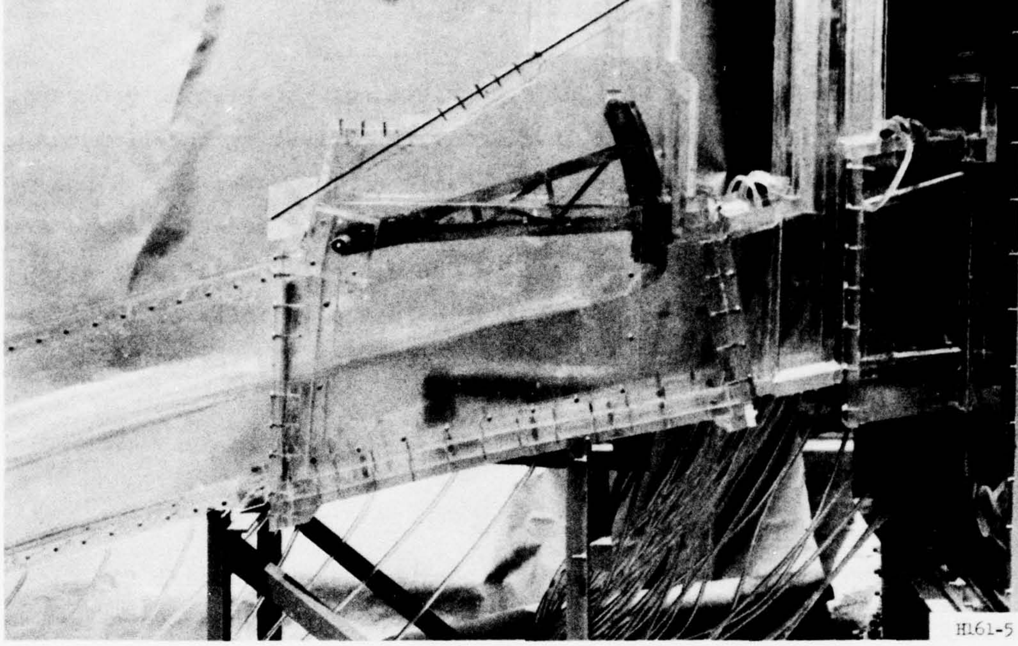
### Existing Sluice

#### Discharge characteristics

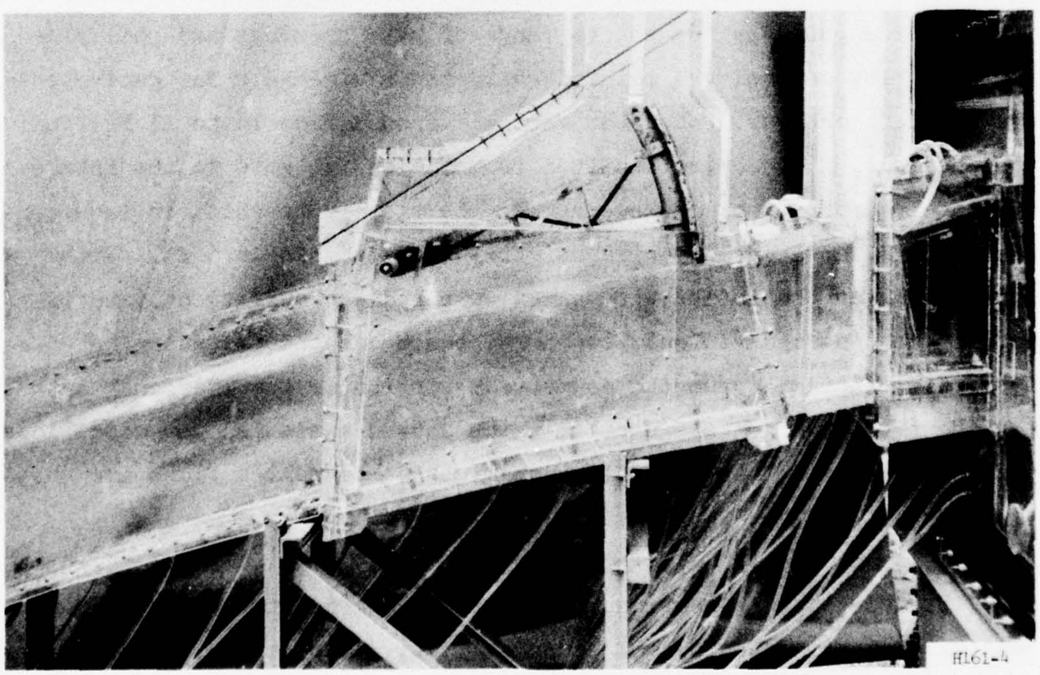
14. The discharge rating curve obtained from the model for partial and full gate openings and normal power pool (el 2459) correlated closely with the prototype rating curve as shown by Plate 4. Free flow (partially filled conduit) conditions existed in the sluice downstream of the sluice gate for the entire range of gate openings and pool elevations. Flow control was maintained by the sluice gate for gate openings of 16 ft or less. When the gate was opened from 16 to 17 ft (full gate opening), flow control shifted from the sluice gate to the intake immediately upstream of the emergency gate slot. The shift in flow control occurred at a gate opening slightly greater than 16.5 ft. With flow control at the intake, pressures were reduced sufficiently to induce air venting and violent flow disturbances in the emergency gate slot. Flow impinged upon the downstream portion of the emergency gate slot above the roof of the sluice, which caused unstable flow conditions in this locality. Gate-controlled and intake-controlled flows are shown in Figures 4a and 4b, respectively.

#### Pressures

15. Piezometer locations throughout the model are shown in Plates 5 and 6. For gate openings of 16 ft or less, all pressures measured upstream of the sluice gate were positive (Tables 1-5); for a 16.5-ft gate opening, some slightly negative pressures were measured (Table 6). With




a. Gate-controlled flow




b. Intake-controlled flow

Figure 4. "As-built" sluice

the sluice gate fully open (intake-controlled flow), negative pressures were observed upstream of the gate, thus indicating probable cavitation (Table 7). Minimum pressures (Plate 7), plotted for a range of pool elevations and gate openings, indicated that sluice gate openings greater than 16 ft would create negative pressures upstream of the sluice gate.

16. Some negative pressures were measured downstream of the sluice gate (Tables 1-7); however, most of the piezometers in this region indicated positive and approximately zero (atmospheric) pressures which seemed quite reasonable for the theoretical parabolic shape. Two pressure transducers were mounted along the invert of the sluiceway to detect high-frequency fluctuations in pressure. The pressure transducers did show positive and negative pressure fluctuations, but the average pressures were approximately zero or slightly positive. Prototype tests conducted during August 1974* revealed that the mean pressures along the sluiceway downstream of the sluice gate varied from zero to the vapor pressure of water (see Plate 6 for prototype pressure cell locations). Because the pressures measured downstream of the model sluice gate with piezometers and pressure cells were not as low as pressures measured in the prototype, the decision was made to install lift joints (see paragraph 10) in the model to determine the effect on pressure conditions.

17. Two lift joint discontinuities and two additional piezometers were installed in the model as shown in Plate 8. Pressures measured with piezometers for various gate openings with lift joints in the model are presented in Tables 8-12. Pressures measured with piezometer 83 were consistent with average pressures obtained from pressure cell 2, which was located in the same vicinity within the prototype sluice. The model indicated that the lift joint discontinuity caused local flow separation and reduced pressure along the invert of the sluice.

18. The average pressures measured downstream of the model sluice gate were not as low as those measured in the prototype because of the

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* E. D. Hart and A. R. Tool, "Sluice Pressures, Gate Vibrations, and Stilling Basin Wall Pressures, Libby Dam, Kootenai River, Montana," Technical Report H-76-17, Oct 1976, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

inability to reproduce local geometric discontinuities and flow separation along the invert and walls of the model. With the magnitude of velocity heads involved, it is quite reasonable to expect pressure fluctuations in the range of those measured during prototype tests when the flow is subjected to surface discontinuities and irregularities.

## Aerator Development

19. The extent of aeration in the model sluice with the as-built conditions was limited primarily to the water surface as shown in Figure 5. Various aerator configurations were constructed and tested in the model to develop a device that would fully aerate the flow on all boundaries without creating adverse flow conditions. The aerators basically consisted of two parts, the slot and the deflector. The purpose of the deflector is to create a low-pressure region over the slot and to prevent water from entering the slot. The purpose of the slot is to provide a passage to permit sufficient flow of air from the gate chamber into the low-pressure region created by the deflector, and thus

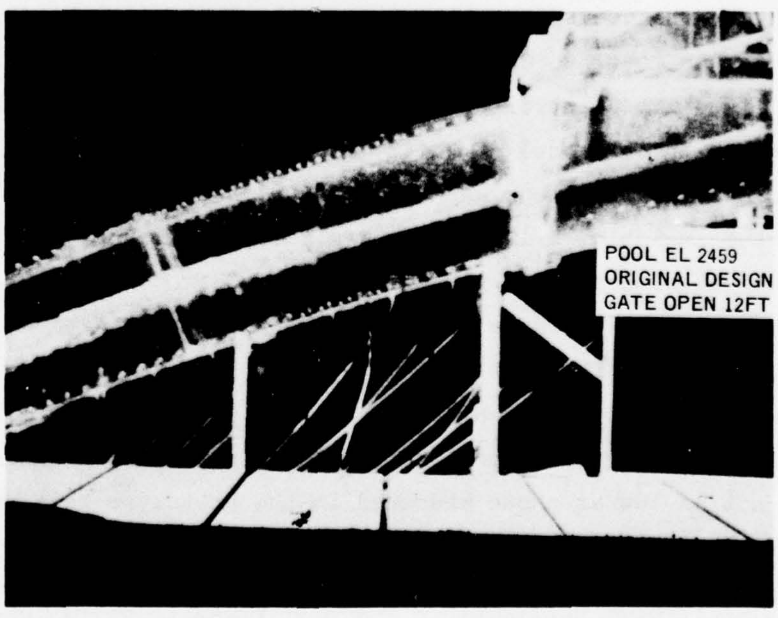


Figure 5. Extent of aeration with the as-built conditions

aerate water flowing along downstream boundaries of the sluice.

20. Because the aerator slot did not affect the water flow conditions, it was sized large enough that airflow was not restricted and was shaped so that water flow did not impinge upon the slot and block the flow of air. Design of a satisfactory deflector that did not create adverse flow conditions was more involved. The various deflector arrangements tested are listed in Table 13. The characteristics of each aerator are discussed in the order shown in Table 13.

Type 1 aerator

21. The type 1 aerator (Plate 9) consisted of 6.0-in.-high deflectors with a deflection angle $\theta$ of 6.34°, 1-on-9 slopes or flares, and 3.0-in.-deep by 4.0-ft-wide slots on the sidewalls and invert. The depth of the slots was made shallow so that structural steel within the concrete would not have to be exposed during prototype installation. The model tests showed that the aerator achieved full aeration of the flow but caused adverse flow conditions characterized by flow striking the roof of the sluice which resulted from excessive deflection of the flow. Although air was successfully supplied by the slot in the model, a deeper slot was considered necessary to assure proper venting in the prototype. A deeper slot meant that structural steel would have to be exposed during prototype installation.

Types 2 and 3 aerators

22. The deflectors of the type 2 aerator (Plate 10) were 3 in. high with similar flare and angle of deflection (1-on-9 slope and 6.34°), and the slots were 2 ft 9 in. deep by 3.0 ft wide. Results from model studies* conducted by the USBR were used to help in the design of this aerator. Flow conditions were improved with the type 2 aerator but were still unsatisfactory due to excessive flow deflection along the sides. In an attempt to reduce bulking of the jet and improve flow conditions, the sidewall deflectors were removed (type 3). This resulted in more

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* D. M. Colgate, "Hydraulic Model Studies of Aeration Devices for Yellowtail Dam Spillway Tunnel, Pick-Sloan Missouri Basin Program, Montana," REC-ERC-71-47, Dec 1971, Bureau of Reclamation, Engineering and Research Center, Denver, Colo.

favorable flow conditions in the sluice; but water impinged upon the sidewall slots, thus preventing aeration along the sidewalls.

Types 4, 5, and 6 aerators

23. To reduce bulking of the jet, the sidewall deflector height of the type 2 aerator was reduced to 1.5 in., as described in Table 13, to create the type 4 aerator. The type 4 aerator provided full aeration on all flow boundaries but created unfavorable and excessive deflection of flow along the sidewalls. The deflection angle for the sidewall deflectors was reduced to 3.18° (1-on-18 slope) for the type 5 aerator. This produced acceptable flow conditions in the sluice; however, some flow and spray did randomly hit the roof, so it was decided that further improvements to the design should be attempted.

24. Sidewall deflectors tapered from a height of 3 in. ($\theta = 3.18°$) at the invert to zero height and deflection at an elevation of 17 ft above the invert (type 6) were tested in an effort to create less flow disturbance along the water surface. The tapered sidewall deflectors caused unfavorable flow conditions and allowed water to impinge upon the sidewall slots at the water surface during large gate openings.

Type 7 aerator

25. The type 7 aerator (Plate 11) was developed by reducing the height of the deflector on the invert of the type 5 aerator to 1.5-in. and the deflection angle to 3.18°. This aerator allowed aeration of all flow boundaries without creating unfavorable flow conditions and was therefore recommended for prototype installation. Flow impingement upon the slots did not occur for most of the expected range of conditions. Flow conditions with the type 7 aerator are shown in Photo 1 for partial and full gate openings. The degree of flow disturbance was much less than that experienced with types 1-6. The type 7 aerator was tested with 17-ft-high sidewall slots which allowed some water to enter the sidewall slots at the water surface for a 17-ft gate opening. The sidewall slots and deflectors should be extended further up the sidewalls as shown by Plate 11 to prevent this occurrence in the prototype.

Type 8 aerator

26. The type 8 aerator (Plate 12) consisted of the same

configuration for the invert slot and deflector and sidewall slots as that of the type 7 aerator. However, for the type 8 aerator, there were no sidewall deflectors and the sidewall slots were partially covered to prevent impingement while allowing aeration along the sidewalls. The sidewall deflectors were removed to achieve better flow conditions. The type 8 aerator provided a small degree of aeration along the sidewalls while allowing good flow conditions in the sluice. Without sidewall deflectors, some water entered the sidewall slots. The degree of aeration along the sidewalls was not sufficient to justify use of this design.

## Intake Modifications

27. During a conference held at WES, it was recommended by the consultants (see Preface) that two modifications be made to the prototype sluices in the vicinity of the emergency gate slot. First, the square blocks of concrete at the top corners of each sluice on the downstream face of the emergency gate slot should be removed by extending the 6-in. offset of the sluice sidewall 2 ft above the roof of the sluice (Plate 13). This modification was made to the model. Second, a steel plate extending 2 ft vertically up the downstream face of the emergency gate slot should be installed across the width of the sluice. The bottom edge of this plate should be welded to the 3/4-in. liner plate that presently forms the roof of the sluice.

28. Two modifications to the roof of the intake were recommended by the consultants for model testing. These model revisions consisted of replacing the section of 1-ft horizontal roof immediately upstream of the emergency gate slot with a sloping section tangent to the upstream roof (modification 1, Plate 13) and with the section sloped to project 1.5 in. into the flow (modification 2, Plate 13). The revisions were tested to determine if pressure conditions in the intake during maximum gate openings could be substantially improved.

29. Pressures observed in the model with the two roof modifications are presented in Tables 14-19 for gate openings of 16, 16.5, and 17 ft. Both revisions provided favorable pressure conditions in the

intake for all gate openings. With the sluice gate fully open, flow control was maintained by the intake immediately upstream of the emergency gate slot as it was with the as-built geometry; however, with the roof restrictions, flow did not impinge and erupt into the roof opening of the emergency gate slot as it did in the original design. A smooth jet passed beneath the emergency gate slot roof opening which allowed more tranquil flow conditions in the vicinity of the emergency gate slot. Flow impinged on the sidewall gate slots with a 17-ft gate opening with both revisions, as shown in Photo 2. Flow separation along the sidewalls downstream of the gate slot resulting from the flow impingement caused a negative pressure region (piezometer 19, Tables 16 and 19) that could possibly produce some cavitation. However, an air-water mixture created in the gate slot by the turbulent action of the flow impingement could provide a cushion sufficient to prevent any cavitation damage that might develop in the region of piezometer 19. Furthermore, the steel liner plate that exists in this portion of the sluice should help minimize damage.

30. There were no significant advantages of modification 2 over modification 1. Roof pressures with modification 2 were slightly higher than with modification 1, but the differences were not sufficient to justify the use of a roof deflector (modification 2). If conditions necessitate operation with a 17-ft gate opening for extended periods, then modification 1 is recommended to prevent excessive cavitation damage that is likely to occur with the existing geometry.

## PART IV: DISCUSSION OF RESULTS

31. The model study of the center sluice of Libby Dam helped to define undesirable hydraulic conditions that have caused cavitation damage of the prototype structure. The 1:20-scale model was used to evaluate and develop various designs of aerators that are needed to prevent cavitation damage in the sluices downstream of the sluice gates. A certain roof modification is suggested to prevent unstable flow and cavitation damage in the roofs of the sluice intakes near the emergency gate slot.

32. The severe damage experienced along the invert and sidewalls of the sluice was attributed to cavitation in high-velocity flow caused by small surface irregularities and discontinuities on the invert which was designed for zero (atmospheric) pressures. However, had the invert been shaped such that pressures were equal to the depth of flow, cavitation (tripped by small surface irregularities) still would have been likely in the high-velocity (130 fps) jet. The best solution to the problem was considered to be aeration of the jet to provide a cushion against damaging pressure fluctuations that occur in cavitating flow.

33. The model was used to develop an aeration device that would provide sufficient aeration along all flow boundaries without adversely altering flow conditions in the sluice. The recommended (type 7) aerator (Plate 11) provided good ventilation of the jet without altering the discharge characteristics and capacity of the sluice. While an aerator inherently caused bulking of the flow, that resulting from the type 7 aerator did not cause the sluiceway to fill with any gate opening. An aerator with greater deflection of the jet was not needed and as demonstrated by the model, this would increase flow disturbances. An aerator with less deflection of the jet might give satisfactory results but would require excessively restrictive tolerances during installation to assure success.

34. The recommended minimum operating conditions with the type 7 aerator are presented in Plate 14. The line therein denotes pool elevations and gate openings that permitted water to flow into the aeration

slots and which would probably impair the effectiveness of the aerator. Conditions above the line shown in Plate 14 should be satisfactory. With gate openings less than 14 ft and pool elevations greater than the minimum pool (el 2287), there was no flow of water into the aerator slots and good aeration was provided. The aerator maintained complete effectiveness for all gate openings with pool elevations greater than el 2320. For pool elevations less than el 2320, jet velocities and the threat of cavitation should be substantially reduced.

35. Air demand of the sluice was increased with the presence of the aerator. Venting occurred through the 4- by 4-ft ventilation conduits and the outlet portal of the sluice. With flow passing over the outlet portal, as with combined sluice and spillway flow, ventilation through the outlet portal was hindered and an increase in air demand through the vent system was observed in the model. Excessive restrictions to the openings of the model vents demonstrated that during large gate openings, the sluice could be made to prime and flow full, creating a siphon action which resulted in unstable flow and extremely low pressures. With combined spillway and sluice flow, the vents of the model sluice had to be restricted to a total opening of less than 5 sq ft to cause complete priming of the siphon. This is only 16 percent of the total available opening (two 4- by 4-ft vents or 32 sq ft) with the existing size of the vents. Thus, the existing ventilation system should provide sufficient air to maintain open channel flow and prevent siphon action from developing. Although the capacity of the vent system should be ample, connected vents are undesirable and it is recommended that modifications be made to provide individual vents to each sluice. Operations with combined spillway and sluice flow should be avoided as much as possible.

36. Modification of the roof of the sluice (Plate 13) to eliminate the 1-ft section of horizontal roof immediately upstream of the emergency gate slot greatly improved pressure and flow conditions in this vicinity with 16.5- and 17-ft gate openings. Because flow control was maintained just upstream of the gate slot with a 17-ft gate opening, there was an undesirable impingement of flow upon the sidewall gate

slots with the revision. However, performance was improved relative to the excessively low pressures and flow disturbances observed in the model with the as-built geometry. Without the modification to the intake roof geometry, the tainter gate openings cannot be allowed to exceed 16 ft without creating low pressures and subsequent cavitation damage in the intake. If the decision is made to modify the roof of the intake, then modification 1 (Plate 13) is recommended. Modification 2 (Plate 13) would unnecessarily restrict the intake opening and reduce the sluice discharge capacity. Operation with a 17-ft gate opening would require revision of the intake roof with modification 1 to prevent cavitation damage from occurring in the intake.

37. With the as-built geometry reproduced in the model, flow control shifted from the sluice gate to the vicinity of the emergency gate slot at some gate opening between 16.5 and 17 ft. Should conditions require gate openings greater than 16.5 ft, it is recommended that the sluice gate be moved as rapidly as feasible to the fully open position to prevent unstable flow conditions that accompany the alternating shift in flow control from the sluice gate to the intake.

38. Downward curving sluices shaped to the profile of a free-falling jet, with the roof raised downstream from the control gate and free-surface flow established, are assumed to have boundary pressures close to atmospheric. However, there may be variations in local average pressures on the order of $\pm 5\%$ (or more) of the velocity head (which may be even higher than the profile design head). These pressure variations result from small boundary irregularities, small differences between prototype and model, difficulties in measuring the small pressures in the model, and other factors. At high heads (say, 250 ft or more) and the resulting high velocities, these local variations (in the negative direction) combined with substantial pressure fluctuations in the turbulent boundary layer may well be enough to induce cavitation. Thus, extreme care should be exercised in the design and construction of such high-velocity passages, including carefully conducted model studies to ensure against the cavitation-inducing pressure conditions.

Table 1

Pressures Throughout Sluice, Sluice Gate Open 1 ft

Pool El 2459 ft msl, Discharge 1200 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 232.0 | 41 | 2.4 |
| 2 | 234.0 | 42 | 1.4 |
| 3 | 236.2 | 43 | 1.9 |
| 4 | 237.6 | 44 | 2.7 |
| 5 | 236.6 | 45 | 2.5 |
| 6 | 236.6 | 46 | 1.7 |
| 7 | 236.9 | 47 | 2.2 |
| 8 | 236.9 | 48 | 1.7 |
| 9 | 238.1 | 49 | 1.9 |
| 10 | 238.5 | 50 | 2.6 |
| 11 | 238.7 | 51 | 1.6 |
| 12 | 239.5 | 52 | 3.9 |
| 13 | 239.9 | 53 | 0.4 |
| 14 | 243.7 | 54 | 3.1 |
| 15 | 245.2 | 55 | 2.5 |
| 16 | 246.0 | 56 | -0.3 |
| 17 | 246.3 | 57 | 2.5 |
| 18 | 247.9 | 58 | 2.2 |
| 19 | 248.5 | 59 | 0.7 |
| 20 | 255.0 | 60 | * |
| 21 | 254.4 | 61 | 6.8 |
| 22 | 254.5 | 62 | 2.2 |
| 23 | 255.3 | 63 | 2.3 |
| 24 | 255.5 | 64 | 1.0 |
| 25 | 256.1 | 65 | ** |
| 26 | 257.1 | 66 | ** |
| 27 | 247.5 | 67 | ** |
| 28 | 238.2 | 68 | ** |
| 29 | 238.2 | 69 | ** |
| 30 | 256.9 | 70 | ** |
| 31 | 249.6 | 71 | ** |
| 32 | 232.1 | 72 | ** |
| 33 | 233.1 | 73 | 0.4 |
| 34 | 249.7 | 74 | 3.4 |
| 35 | 249.7 | 75 | 0.4 |
| 36 | -1.8 | 76 | 1.5 |
| 37 | -3.4 | 77 | 2.2 |
| 38 | 3.2 | 78 | 253.6 |
| 39 | 8.8 | 79 | 253.5 |
| 40 | -2.0 | 80 | 240.5 |
| | | 81 | * |
| | | 82 | * |

* Piezometer inoperative.

** Piezometer above water surface.

Table 2

Pressures Throughout Sluice, Sluice Gate Open 4 ft

Pool El 2459 ft msl, Discharge 3500 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 231.5 | 41 | 3.4 |
| 2 | 231.5 | 42 | 1.0 |
| 3 | 231.2 | 43 | 2.2 |
| 4 | 200.4 | 44 | 4.0 |
| 5 | 230.1 | 45 | 2.1 |
| 6 | 230.9 | 46 | 1.6 |
| 7 | 231.2 | 47 | 2.7 |
| 8 | 231.2 | 48 | 1.2 |
| 9 | 233.1 | 49 | 2.9 |
| 10 | 236.3 | 50 | 4.1 |
| 11 | 235.7 | 51 | 1.6 |
| 12 | 235.0 | 52 | 6.9 |
| 13 | 235.4 | 53 | -1.8 |
| 14 | 241.5 | 54 | 4.3 |
| 15 | 239.7 | 55 | 3.7 |
| 16 | 240.5 | 56 | -0.5 |
| 17 | 239.8 | 57 | 2.9 |
| 18 | 242.9 | 58 | 4.1 |
| 19 | 240.7 | 59 | -0.1 |
| 20 | 252.8 | 60 | * |
| 21 | 250.7 | 61 | 4.0 |
| 22 | 247.8 | 62 | 2.7 |
| 23 | 247.6 | 63 | 3.8 |
| 24 | 247.5 | 64 | 0.6 |
| 25 | 248.1 | 65 | 1.1 |
| 26 | 246.1 | 66 | 1.9 |
| 27 | 240.2 | 67 | 1.1 |
| 28 | 230.9 | 68 | 0.4 |
| 29 | 230.9 | 69 | 1.5 |
| 30 | 235.8 | 70 | 0.1 |
| 31 | 171.6 | 71 | 1.4 |
| 32 | 239.1 | 72 | 1.4 |
| 33 | 240.1 | 73 | -2.0 |
| 34 | 241.5 | 74 | 5.1 |
| 35 | 235.2 | 75 | 3.4 |
| 36 | 19.7 | 76 | 4.3 |
| 37 | 3.7 | 77 | 3.7 |
| 38 | 3.1 | 78 | 249.1 |
| 39 | 5.8 | 79 | 245.5 |
| 40 | -6.0 | 80 | 232.5 |
| | | 81 | * |
| | | 82 | * |

* Piezometer inoperative.

Table 3

Pressures Throughout Sluice, Sluice Gate Open 8 ft

Pool El 2459 ft msl, Discharge 5650 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 220.0 | 41 | 3.9 |
| 2 | 216.5 | 42 | 1.0 |
| 3 | 209.9 | 43 | 2.2 |
| 4 | 182.6 | 44 | 3.7 |
| 5 | 210.6 | 45 | 4.8 |
| 6 | 210.6 | 46 | 1.2 |
| 7 | 210.9 | 47 | 3.8 |
| 8 | 213.7 | 48 | 0.7 |
| 9 | 225.1 | 49 | 1.1 |
| 10 | 221.1 | 50 | 4.6 |
| 11 | 220.1 | 51 | 0.1 |
| 12 | 215.0 | 52 | 7.9 |
| 13 | 217.0 | 53 | -3.5 |
| 14 | 229.7 | 54 | 4.3 |
| 15 | 219.9 | 55 | 4.2 |
| 16 | 219.5 | 56 | 0.5 |
| 17 | 218.0 | 57 | 2.5 |
| 18 | 225.3 | 58 | 4.7 |
| 19 | 217.1 | 59 | -0.1 |
| 20 | 244.8 | 60 | * |
| 21 | 239.6 | 61 | 3.8 |
| 22 | 228.7 | 62 | 3.7 |
| 23 | 225.6 | 63 | 4.8 |
| 24 | 224.4 | 64 | 0.0 |
| 25 | 223.5 | 65 | 0.9 |
| 26 | 221.9 | 66 | 3.4 |
| 27 | 219.3 | 67 | 1.1 |
| 28 | 216.7 | 68 | 0.4 |
| 29 | 221.7 | 69 | 3.1 |
| 30 | 192.2 | 70 | 1.0 |
| 31 | 122.6 | 71 | 3.6 |
| 32 | 231.1 | 72 | 6.5 |
| 33 | 233.1 | 73 | -1.6 |
| 34 | 217.9 | 74 | 7.0 |
| 35 | 178.3 | 75 | 4.4 |
| 36 | 37.9 | 76 | 6.1 |
| 37 | 7.6 | 77 | 1.3 |
| 38 | 3.6 | 78 | 237.2 |
| 39 | 7.9 | 79 | 224.3 |
| 40 | -6.0 | 80 | 205.3 |
| | | 81 | * |
| | | 82 | * |

* Piezometer inoperative.

Table 4

Pressures Throughout Sluice, Sluice Gate Open 14 ft

Pool El 2459 ft msl, Discharge 11,200 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 193.8 | 41 | 4.4 |
| 2 | 168.5 | 42 | 0.5 |
| 3 | 137.7 | 43 | 2.2 |
| 4 | 116.6 | 44 | 4.7 |
| 5 | * | 45 | 5.3 |
| 6 | 139.1 | 46 | 1.2 |
| 7 | 139.4 | 47 | 4.0 |
| 8 | 144.7 | 48 | 0.0 |
| 9 | 191.1 | 49 | 0.9 |
| 10 | 167.5 | 50 | 6.4 |
| 11 | 163.2 | 51 | 0.6 |
| 12 | 138.5 | 52 | 11.9 |
| 13 | 141.2 | 53 | -4.6 |
| 14 | 190.5 | 54 | 5.1 |
| 15 | 150.2 | 55 | 5.2 |
| 16 | 149.0 | 56 | 1.0 |
| 17 | 144.3 | 57 | 2.0 |
| 18 | 162.4 | 58 | 4.7 |
| 19 | 135.8 | 59 | -0.6 |
| 20 | 215.8 | 60 | * |
| 21 | 198.2 | 61 | 2.5 |
| 22 | 162.3 | 62 | 4.5 |
| 23 | 150.6 | 63 | 5.8 |
| 24 | 145.8 | 64 | -0.7 |
| 25 | 145.1 | 65 | 0.9 |
| 26 | 136.4 | 66 | 4.4 |
| 27 | 147.2 | 67 | 0.1 |
| 28 | 146.4 | 68 | -0.9 |
| 29 | 140.9 | 69 | 4.3 |
| 30 | 115.8 | 70 | 1.0 |
| 31 | 83.1 | 71 | 6.4 |
| 32 | 179.1 | 72 | 1.1 |
| 33 | 194.6 | 73 | -0.2 |
| 34 | 139.2 | 74 | 5.4 |
| 35 | 92.2 | 75 | 5.4 |
| 36 | 43.7 | 76 | 6.5 |
| 37 | 17.5 | 77 | 0.2 |
| 38 | 8.1 | 78 | 192.4 |
| 39 | 11.8 | 79 | 146.0 |
| 40 | -7.7 | 80 | 116.0 |
| | | 81 | 157.0 |
| | | 82 | 130.7 |

* Piezometer inoperative.

Table 5

Pressures Throughout Sluice, Sluice Gate Open 16 ft

Pool El 2459 ft msl, Discharge 15,700 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 174.0 | 41 | 4.9 |
| 2 | 104.5 | 42 | 1.0 |
| 3 | 79.7 | 43 | 2.2 |
| 4 | 42.6 | 44 | 4.7 |
| 5 | 75.6 | 45 | 6.3 |
| 6 | 79.6 | 46 | 1.7 |
| 7 | 79.9 | 47 | 4.0 |
| 8 | 88.9 | 48 | 0.0 |
| 9 | 173.1 | 49 | 0.7 |
| 10 | 120.5 | 50 | 5.8 |
| 11 | 115.7 | 51 | 0.6 |
| 12 | 69.0 | 52 | 11.9 |
| 13 | 71.0 | 53 | -3.9 |
| 14 | 159.7 | 54 | 5.6 |
| 15 | 95.7 | 55 | 5.5 |
| 16 | 90.5 | 56 | 1.5 |
| 17 | 84.8 | 57 | 3.3 |
| 18 | 110.0 | 58 | 5.0 |
| 19 | 70.0 | 59 | -0.1 |
| 20 | 194.3 | 60 | * |
| 21 | 168.7 | 61 | 4.8 |
| 22 | 108.8 | 62 | 2.7 |
| 23 | 94.6 | 63 | 5.6 |
| 24 | 84.0 | 64 | -1.0 |
| 25 | 86.6 | 65 | 1.4 |
| 26 | 82.1 | 66 | 4.9 |
| 27 | 88.7 | 67 | 10.6 |
| 28 | 84.9 | 68 | -1.1 |
| 29 | 79.9 | 69 | 5.0 |
| 30 | 70.3 | 70 | 1.3 |
| 31 | 55.1 | 71 | 7.4 |
| 32 | 106.6 | 72 | 1.1 |
| 33 | 154.6 | 73 | -1.0 |
| 34 | 87.7 | 74 | 6.4 |
| 35 | 60.2 | 75 | 5.9 |
| 36 | 32.7 | 76 | 7.2 |
| 37 | 17.2 | 77 | 2.7 |
| 38 | 9.1 | 78 | 162.1 |
| 39 | 12.3 | 79 | 82.5 |
| 40 | -6.5 | 80 | 45.5 |
| | | 81 | 107.5 |
| | | 82 | 63.7 |

* Piezometer inoperative.

Table 6

Pressures Throughout Sluice, Sluice Gate Open 16.5 ft

Pool El 2459 ft msl, Discharge 17,800 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 159.5 | 41 | 4.7 |
| 2 | 109.0 | 42 | 0.9 |
| 3 | 46.7 | 43 | 2.3 |
| 4 | -2.4 | 44 | 4.8 |
| 5 | * | 45 | 10.4 |
| 6 | 47.3 | 46 | 1.4 |
| 7 | 48.2 | 47 | 2.6 |
| 8 | 58.5 | 48 | -1.3 |
| 9 | 147.1 | 49 | -0.1 |
| 10 | 96.5 | 50 | 5.6 |
| 11 | 89.5 | 51 | 0.7 |
| 12 | 31.5 | 52 | 11.2 |
| 13 | 33.2 | 53 | -3.9 |
| 14 | 140.7 | 54 | 5.6 |
| 15 | 65.7 | 55 | 5.7 |
| 16 | 54.4 | 56 | 2.0 |
| 17 | 52.7 | 57 | 2.5 |
| 18 | 82.6 | 58 | 4.6 |
| 19 | 32.3 | 59 | -1.0 |
| 20 | 180.8 | 60 | * |
| 21 | 149.6 | 61 | 3.9 |
| 22 | 79.7 | 62 | 4.3 |
| 23 | 55.9 | 63 | 5.3 |
| 24 | 51.3 | 64 | -0.3 |
| 25 | 59.2 | 65 | 1.5 |
| 26 | 51.9 | 66 | 4.4 |
| 27 | 56.2 | 67 | 0.1 |
| 28 | 57.9 | 68 | -0.9 |
| 29 | 49.2 | 69 | 5.3 |
| 30 | 50.2 | 70 | 1.2 |
| 31 | 38.1 | 71 | 7.9 |
| 32 | 64.4 | 72 | 1.5 |
| 33 | 103.6 | 73 | 1.0 |
| 34 | 58.6 | 74 | 6.4 |
| 35 | 40.1 | 75 | 5.6 |
| 36 | 22.0 | 76 | 7.3 |
| 37 | 13.3 | 77 | 0.4 |
| 38 | 8.6 | 78 | 140.1 |
| 39 | 13.3 | 79 | 47.0 |
| 40 | -7.1 | 80 | -6.5 |
| | | 81 | 79.5 |
| | | 82 | 24.7 |

* Piezometer inoperative.

Table 7

Pressures Throughout Sluice, Sluice Gate Open 17 ft

Pool El 2459 ft msl, Discharge 20,200 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 138.0 | 41 | 4.9 |
| 2 | 76.0 | 42 | 1.5 |
| 3 | 1.7 | 43 | 2.8 |
| 4 | -33.9 | 44 | 4.2 |
| 5 | -3.9 | 45 | 4.8 |
| 6 | 2.1 | 46 | 1.7 |
| 7 | 2.4 | 47 | 4.2 |
| 8 | 14.4 | 48 | 9.2 |
| 9 | 93.1 | 49 | 10.4 |
| 10 | 63.5 | 50 | 6.1 |
| 11 | 48.7 | 51 | 1.6 |
| 12 | -20.0 | 52 | 12.5 |
| 13 | -19.6 | 53 | -3.6 |
| 14 | 113.7 | 54 | 6.1 |
| 15 | 20.7 | 55 | 6.2 |
| 16 | 12.5 | 56 | 2.0 |
| 17 | 7.8 | 57 | 3.0 |
| 18 | 37.4 | 58 | 5.2 |
| 19 | -16.0 | 59 | -0.1 |
| 20 | 161.3 | 60 | * |
| 21 | 121.7 | 61 | 4.3 |
| 22 | 36.8 | 62 | 4.7 |
| 23 | 9.6 | 63 | 5.8 |
| 24 | 3.5 | 64 | 0.0 |
| 25 | 10.1 | 65 | 0.4 |
| 26 | 10.1 | 66 | 3.9 |
| 27 | 11.2 | 67 | 0.1 |
| 28 | 12.3 | 68 | -1.9 |
| 29 | 2.9 | 69 | 5.3 |
| 30 | 9.3 | 70 | 2.0 |
| 31 | 12.1 | 71 | 7.4 |
| 32 | 4.6 | 72 | 2.2 |
| 33 | -4.4 | 73 | 0.5 |
| 34 | 16.7 | 74 | 6.4 |
| 35 | 6.2 | 75 | 4.4 |
| 36 | 6.7 | 76 | 7.0 |
| 37 | 6.7 | 77 | 3.2 |
| 38 | 7.1 | 78 | 112.1 |
| 39 | 12.3 | 79 | 0.5 |
| 40 | -6.0 | 80 | -50.5 |
| | | 81 | 49.5 |
| | | 82 | -20.3 |

* Piezometer inoperative.

Table 8

Pressures Downstream of Sluice Gate with Lift Joints

Sluice Gate Open 1 ft, Pool El 2459 ft msl

Discharge 1200 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 37 | 3.7 | 59 | -0.1 |
| 38 | 3.6 | 60 | * |
| 39 | 3.8 | 61 | 4.8 |
| 40 | -3.5 | 62 | 1.7 |
| 41 | -4.6 | 63 | 1.8 |
| 42 | 4.5 | 64 | 0.5 |
| 43 | -0.8 | 65 | ** |
| 44 | -3.8 | 66 | ** |
| 45 | 1.8 | 67 | ** |
| 46 | 1.2 | 68 | ** |
| 47 | 1.7 | 69 | ** |
| 48 | 1.7 | 70 | ** |
| 49 | 1.6 | 71 | ** |
| 50 | 2.6 | 72 | ** |
| 51 | 1.6 | 73 | 12.0 |
| 52 | 3.4 | 74 | -2.6 |
| 53 | -0.1 | 75 | 1.2 |
| 54 | 3.1 | 76 | 1.8 |
| 55 | 2.2 | 77 | 1.4 |
| 56 | -1.0 | 83 | -1.9 |
| 57 | 2.5 | 84 | 0.4 |
| 58 | 2.2 | | |

* Piezometer inoperative.
** Piezometer above water surface.

Table 9

Pressures Downstream of Sluice Gate with Lift Joints

Sluice Gate Open 4 ft, Pool El 2459 ft msl

Discharge 3500 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 37 | 3.2 | 59 | -0.1 |
| 38 | 3.6 | 60 | * |
| 39 | 5.3 | 61 | -0.2 |
| 40 | -6.0 | 62 | 2.2 |
| 41 | -2.1 | 63 | 2.8 |
| 42 | 4.5 | 64 | 0.5 |
| 43 | 0.2 | 65 | 0.4 |
| 44 | -2.3 | 66 | 0.9 |
| 45 | 1.8 | 67 | 0.1 |
| 46 | 0.7 | 68 | 0.1 |
| 47 | 1.7 | 69 | 0.8 |
| 48 | 0.7 | 70 | 0.5 |
| 49 | 0.9 | 71 | 0.9 |
| 50 | 3.6 | 72 | 0.6 |
| 51 | 1.1 | 73 | 13.0 |
| 52 | 5.9 | 74 | 5.4 |
| 53 | -1.1 | 75 | 3.4 |
| 54 | 3.6 | 76 | 5.5 |
| 55 | 2.7 | 77 | 2.2 |
| 56 | -1.5 | 83 | -8.9 |
| 57 | 2.5 | 84 | -1.4 |
| 58 | 2.7 | | |

* Piezometer inoperative.

Table 10

Pressures Downstream of Sluice Gate with Lift Joints

Sluice Gate Open 8 ft, Pool El 2459 ft msl

Discharge 5650 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 37 | 6.7 | 59 | -0.1 |
| 38 | 3.6 | 60 | * |
| 39 | 7.3 | 61 | -1.7 |
| 40 | -9.5 | 62 | 3.2 |
| 41 | -0.1 | 63 | 3.8 |
| 42 | 4.0 | 64 | 0.0 |
| 43 | 0.2 | 65 | 0.9 |
| 44 | -1.3 | 66 | 3.9 |
| 45 | 2.8 | 67 | 0.6 |
| 46 | 0.2 | 68 | -0.4 |
| 47 | 2.2 | 69 | 3.8 |
| 48 | 0.2 | 70 | 0.0 |
| 49 | 0.4 | 71 | 4.9 |
| 50 | 4.6 | 72 | 1.1 |
| 51 | 0.1 | 73 | 10.5 |
| 52 | 7.4 | 74 | 6.9 |
| 53 | -2.6 | 75 | 4.0 |
| 54 | 4.6 | 76 | 6.5 |
| 55 | 4.2 | 77 | 0.7 |
| 56 | -0.5 | 83 | -9.9 |
| 57 | 1.5 | 84 | -0.9 |
| 58 | 4.7 | | |

* Piezometer inoperative.

Table 11

Pressures Downstream of Sluice Gate with Lift Joints

Sluice Gate Open 14 ft, Pool El 2459 ft msl

Discharge 11,200 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 37 | 17.20 | 59 | -0.1 |
| 38 | 8.10 | 60 | * |
| 39 | 10.80 | 61 | -2.2 |
| 40 | -11.0 | 62 | 3.7 |
| 41 | 1.4 | 63 | 4.3 |
| 42 | 5.0 | 64 | -1.0 |
| 43 | -0.3 | 65 | 0.4 |
| 44 | 0.7 | 66 | 4.4 |
| 45 | 2.3 | 67 | 0.1 |
| 46 | 0.2 | 68 | -0.9 |
| 47 | 3.2 | 69 | 4.3 |
| 48 | -0.3 | 70 | 0.5 |
| 49 | -0.1 | 71 | 6.4 |
| 50 | 5.6 | 72 | 0.1 |
| 51 | -0.4 | 73 | 12.0 |
| 52 | 9.4 | 74 | 8.4 |
| 53 | -3.6 | 75 | 5.4 |
| 54 | 5.1 | 76 | 6.5 |
| 55 | 4.7 | 77 | 0.2 |
| 56 | 0.5 | 83 | -10.4 |
| 57 | 1.5 | 84 | -0.4 |
| 58 | 4.7 | | |

* Piezometer inoperative.

Table 12

Pressures Downstream of Sluice Gate with Lift Joints

Sluice Gate Open 17 ft, Pool El 2459 ft msl

Discharge 20,200 cfs

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 37 | 5.7 | 59 | -0.1 |
| 38 | 7.1 | 60 | * |
| 39 | 12.3 | 61 | -0.2 |
| 40 | -10.0 | 62 | 4.2 |
| 41 | 1.4 | 63 | 4.8 |
| 42 | 5.5 | 64 | -1.0 |
| 43 | 1.7 | 65 | 0.9 |
| 44 | 1.2 | 66 | 4.4 |
| 45 | 3.3 | 67 | 0.1 |
| 46 | 1.2 | 68 | -0.9 |
| 47 | 3.7 | 69 | 4.8 |
| 48 | -0.3 | 70 | 1.5 |
| 49 | -0.1 | 71 | 7.4 |
| 50 | 7.0 | 72 | 1.1 |
| 51 | 1.1 | 73 | 11.0 |
| 52 | 11.4 | 74 | 8.9 |
| 53 | -2.6 | 75 | 5.9 |
| 54 | 5.6 | 76 | 7.5 |
| 55 | 5.7 | 77 | 0.7 |
| 56 | 1.5 | 83 | -9.4 |
| 57 | 2.5 | 84 | 0.1 |
| 58 | 5.2 | | |

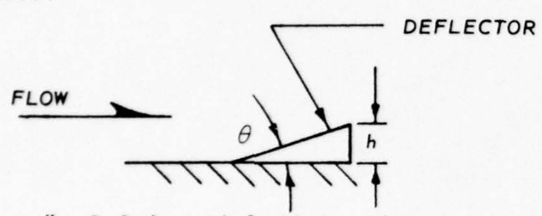
* Piezometer inoperative.

Table 13

Aerator Characteristics

| Aerator No. | Bottom Deflector | | Slide Deflector | | Flow Impinged upon Slot | Water Flow Conditions in Sluice | Aeration of Flow Boundaries |
|---|---|---|---|---|---|---|---|
| | h, in. | θ, degrees | h, in. | θ, degrees | | | |
| 1 | 6.0 | 6.34 | 6.0 | 6.34 | No | Unacceptable | Complete |
| 2 | 3.0 | 6.34 | 3.0 | 6.34 | No | Unfavorable | Complete |
| 3 | 3.0 | 6.34 | 0.0 | 0.0 | Yes, on sides | Good except for flow impingement | Did not aerate sides |
| 4 | 3.0 | 6.34 | 1.5 | 6.34 | No | Unfavorable | Complete |
| 5 | 3.0 | 6.34 | 1.5 | 3.18 | No | Acceptable | Complete |
| 6 | 3.0 | 6.34 | 3.0 At bottom tapered to 0.0 in. at top* | 3.18 | Small amount on sides near surface | Unfavorable | Complete |
| 7 | 1.5 | 3.18 | 1.5 | 3.18 | No | Favorable | Complete |
| 8 | 1.5 | 3.18 | 0.0 With 3-in. opening in side plate covering the slot | 0.0 | Some into right side | Very desirable | Complete on bottom but only small amount on sides |

Note:




* 3.0 in. at bottom, etc.

Table 14

Pressures in Sluice Intake, Roof Modification 1

Sluice Gate Open 16 ft, Pool El 2459 ft msl

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 170.0 | 21 | 164.7 |
| 2 | 129.5 | 22 | 104.3 |
| 3 | 82.7 | 23 | 83.6 |
| 4 | * | 24 | 80.2 |
| 5 | * | 25 | 88.1 |
| 6 | 60.1 | 26 | 84.1 |
| 7 | 59.9 | 27 | 77.2 |
| 8 | 59.4 | 28 | 63.9 |
| 9 | 49.1 | 29 | 60.4 |
| 10 | 95.5 | 30 | 69.3 |
| 11 | 115.7 | 31 | 55.1 |
| 12 | 83.0 | 32 | 101.6 |
| 13 | 74.9 | 33 | 145.6 |
| 14 | 156.7 | 34 | 82.7 |
| 15 | 92.2 | 35 | 57.7 |
| 16 | 78.5 | 78 | 154.6 |
| 17 | 69.3 | 79 | 76.5 |
| 18 | 122.4 | 80 | 73.5 |
| 19 | 66.5 | 81 | 109.0 |
| 20 | 190.8 | 82 | 70.7 |

* Piezometer inoperative.

Table 15

Pressures in Sluice Intake, Roof Modification 1

Sluice Gate Open 16.5 ft, Pool El 2459 ft msl

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 159.0 | 21 | 147.7 |
| 2 | 108.5 | 22 | 75.8 |
| 3 | 52.7 | 23 | 50.1 |
| 4 | * | 24 | 48.5 |
| 5 | * | 25 | 57.1 |
| 6 | 24.6 | 26 | 55.1 |
| 7 | 23.9 | 27 | 44.2 |
| 8 | 23.4 | 28 | 29.4 |
| 9 | 18.1 | 29 | 23.9 |
| 10 | 63.5 | 30 | 44.3 |
| 11 | 87.7 | 31 | 39.1 |
| 12 | 48.0 | 32 | 60.1 |
| 13 | 37.4 | 33 | 93.1 |
| 14 | 140.7 | 34 | 53.7 |
| 15 | 61.7 | 35 | 37.7 |
| 16 | 44.5 | 78 | 136.1 |
| 17 | 32.8 | 79 | 41.5 |
| 18 | 100.4 | 80 | 41.0 |
| 19 | 30.5 | 81 | 85.5 |
| 20 | 180.3 | 82 | 38.7 |

* Piezometer inoperative.

Table 16

Pressures in Sluice Intake, Roof Modification 1

Sluice Gate Open 17 ft, Pool El 2459 ft msl

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 146.0 | 21 | 128.7 |
| 2 | 87.5 | 22 | 44.8 |
| 3 | 22.7 | 23 | 14.6 |
| 4 | * | 24 | 11.0 |
| 5 | * | 25 | 21.6 |
| 6 | ** | 26 | 22.6 |
| 7 | ** | 27 | 6.2 |
| 8 | ** | 28 | ** |
| 9 | ** | 29 | ** |
| 10 | ** | 30 | 15.3 |
| 11 | ** | 31 | 18.1 |
| 12 | 4.0 | 32 | 3.6 |
| 13 | 3.4 | 33 | 5.6 |
| 14 | 121.7 | 34 | 19.7 |
| 15 | 29.7 | 35 | 11.7 |
| 16 | 7.5 | 78 | 115.1 |
| 17 | ** | 79 | 4.0 |
| 18 | 70.4 | 80 | 11.5 |
| 19 | -11.0 | 81 | 59.0 |
| 20 | 165.3 | 82 | 5.2 |

* Piezometer inoperative.

** Piezometer not submerged or above water surface.

Table 17

Pressures in Sluice Intake, Roof Modification 2

Sluice Gate Open 16 ft, Pool El 2459 ft msl

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 169.0 | 21 | 162.2 |
| 2 | 127.5 | 22 | 108.8 |
| 3 | 84.7 | 23 | 79.1 |
| 4 | * | 24 | 76.5 |
| 5 | * | 25 | 84.6 |
| 6 | 50.1 | 26 | 81.1 |
| 7 | 49.9 | 27 | 71.7 |
| 8 | 49.9 | 28 | 52.4 |
| 9 | 50.1 | 29 | 50.4 |
| 10 | 58.5 | 30 | 66.3 |
| 11 | 76.2 | 31 | 53.1 |
| 12 | 85.0 | 32 | 96.6 |
| 13 | 74.4 | 33 | 136.6 |
| 14 | 155.2 | 34 | 79.2 |
| 15 | 88.2 | 35 | 55.2 |
| 16 | 70.5 | 78 | 152.1 |
| 17 | 58.3 | 79 | 71.0 |
| 18 | 121.9 | 80 | 51.5 |
| 19 | 61.5 | 81 | 108.0 |
| 20 | 189.8 | 82 | 71.2 |

* Piezometer inoperative.

Table 18

Pressures in Sluice Intake, Roof Modification 2

Sluice Gate Open 16.5 ft, Pool El 2459 ft msl

| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 156.5 | 21 | 145.7 |
| 2 | 106.5 | 22 | 71.8 |
| 3 | 54.2 | 23 | 145.1 |
| 4 | * | 24 | 43.5 |
| 5 | * | 25 | 54.1 |
| 6 | 13.1 | 26 | 52.6 |
| 7 | 13.4 | 27 | 38.2 |
| 8 | 11.9 | 28 | 16.4 |
| 9 | 12.6 | 29 | 13.4 |
| 10 | 23.5 | 30 | 41.8 |
| 11 | 40.7 | 31 | 38.1 |
| 12 | 51.5 | 32 | 54.6 |
| 13 | 38.4 | 33 | 85.1 |
| 14 | 137.7 | 34 | 50.7 |
| 15 | 57.7 | 35 | 35.2 |
| 16 | 34.5 | 78 | 133.6 |
| 17 | 21.8 | 79 | 36.0 |
| 18 | 97.4 | 80 | 15.0 |
| 19 | 25.5 | 81 | 83.5 |
| 20 | 178.3 | 82 | 39.2 |

* Piezometer inoperative.

Table 19

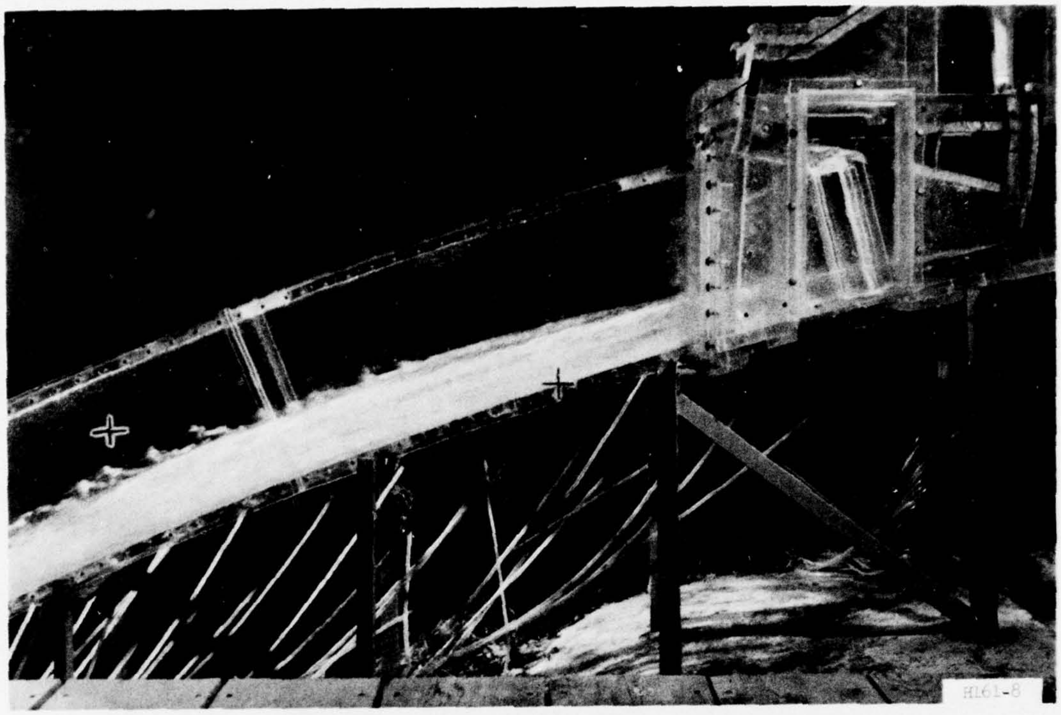
Pressures in Sluice Intake, Roof Modification 2

Sluice Gate Open 17 ft, Pool El 2459 ft msl

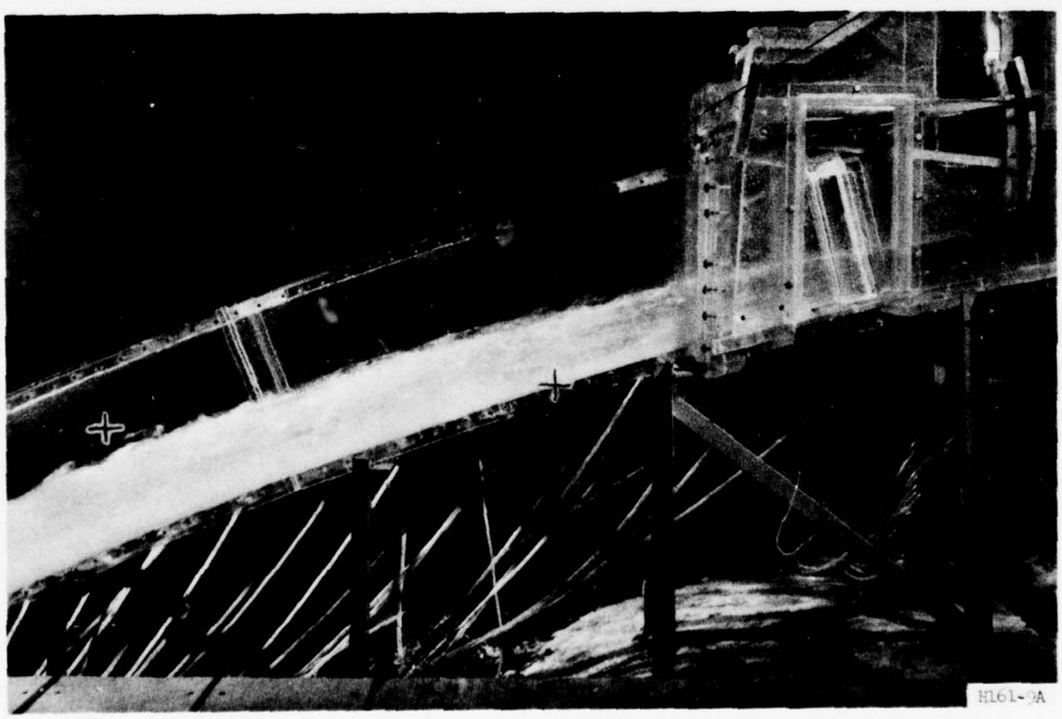
| Piezometer No. | Pressure Feet of Water | Piezometer No. | Pressure Feet of Water |
|---|---|---|---|
| 1 | 148.0 | 21 | 132.2 |
| 2 | 91.5 | 22 | 49.3 |
| 3 | 33.7 | 23 | 18.6 |
| 4 | * | 24 | 14.0 |
| 5 | * | 25 | 25.1 |
| 6 | ** | 26 | 23.6 |
| 7 | ** | 27 | 9.2 |
| 8 | ** | 28 | ** |
| 9 | ** | 29 | ** |
| 10 | ** | 30 | 16.3 |
| 11 | ** | 31 | 18.6 |
| 12 | ** | 32 | 3.1 |
| 13 | ** | 33 | 5.6 |
| 14 | 125.7 | 34 | 19.7 |
| 15 | 34.2 | 35 | 12.2 |
| 16 | 11.5 | 78 | 118.6 |
| 17 | -4.2 | 79 | 3.0 |
| 18 | 70.9 | 80 | 2.5 |
| 19 | -9.5 | 81 | 66.5 |
| 20 | 168.3 | 82 | 17.7 |

* Piezometer inoperative.

** Piezometer not submerged or above water surface.

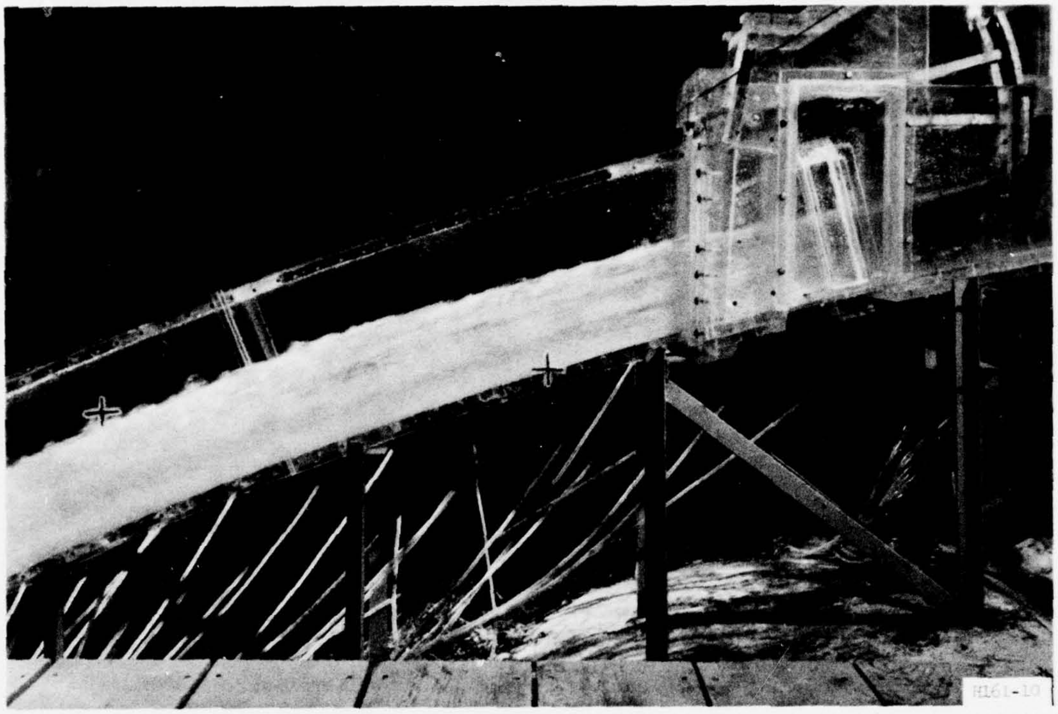



a. Discharge 3500 cfs; 4-ft gate opening

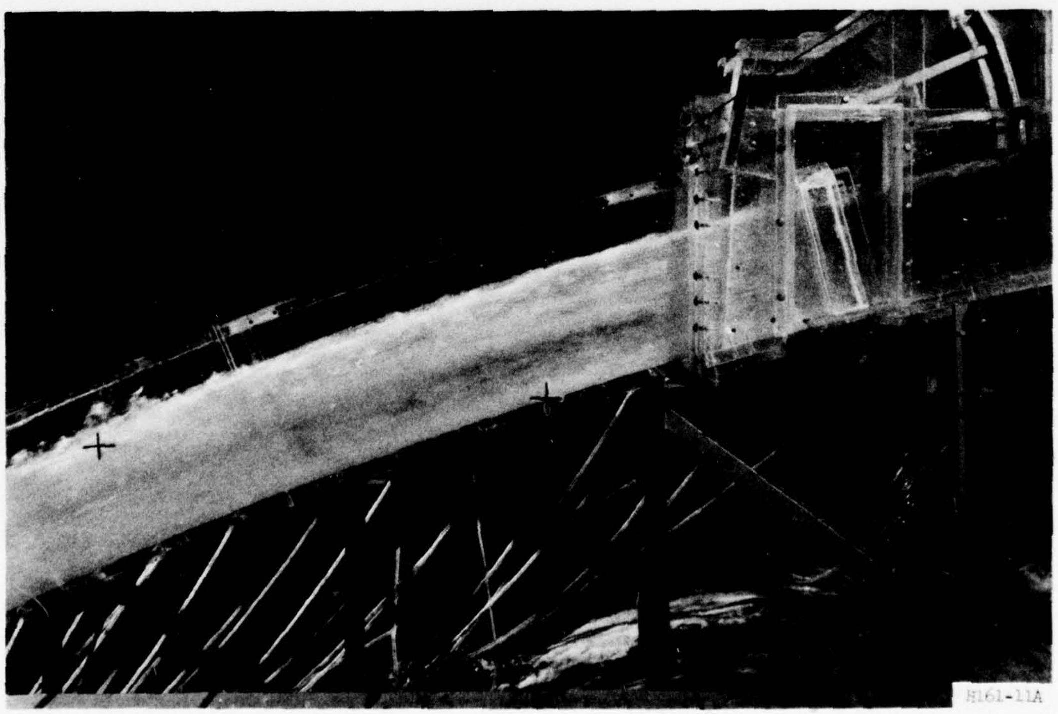



b. Discharge 5650 cfs; 8-ft gate opening

Photo 1. Flow conditions with the type 7 aerator for pool el 2459 (sheet 1 of 3)

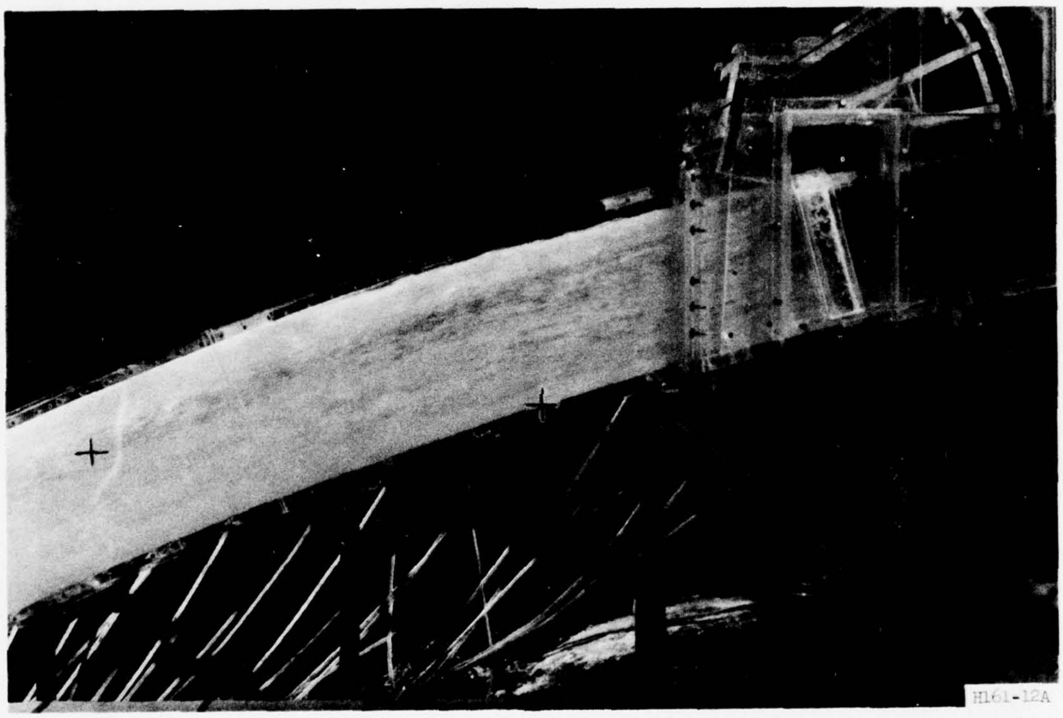



c. Discharge 8,800 cfs; 12-ft gate opening




d. Discharge 15,700 cfs; 16-ft gate opening

Photo 1 (sheet 2 of 3)



e. Discharge 20,200 cfs; 17-ft gate opening (fully open)

Photo 1 (sheet 3 of 3)

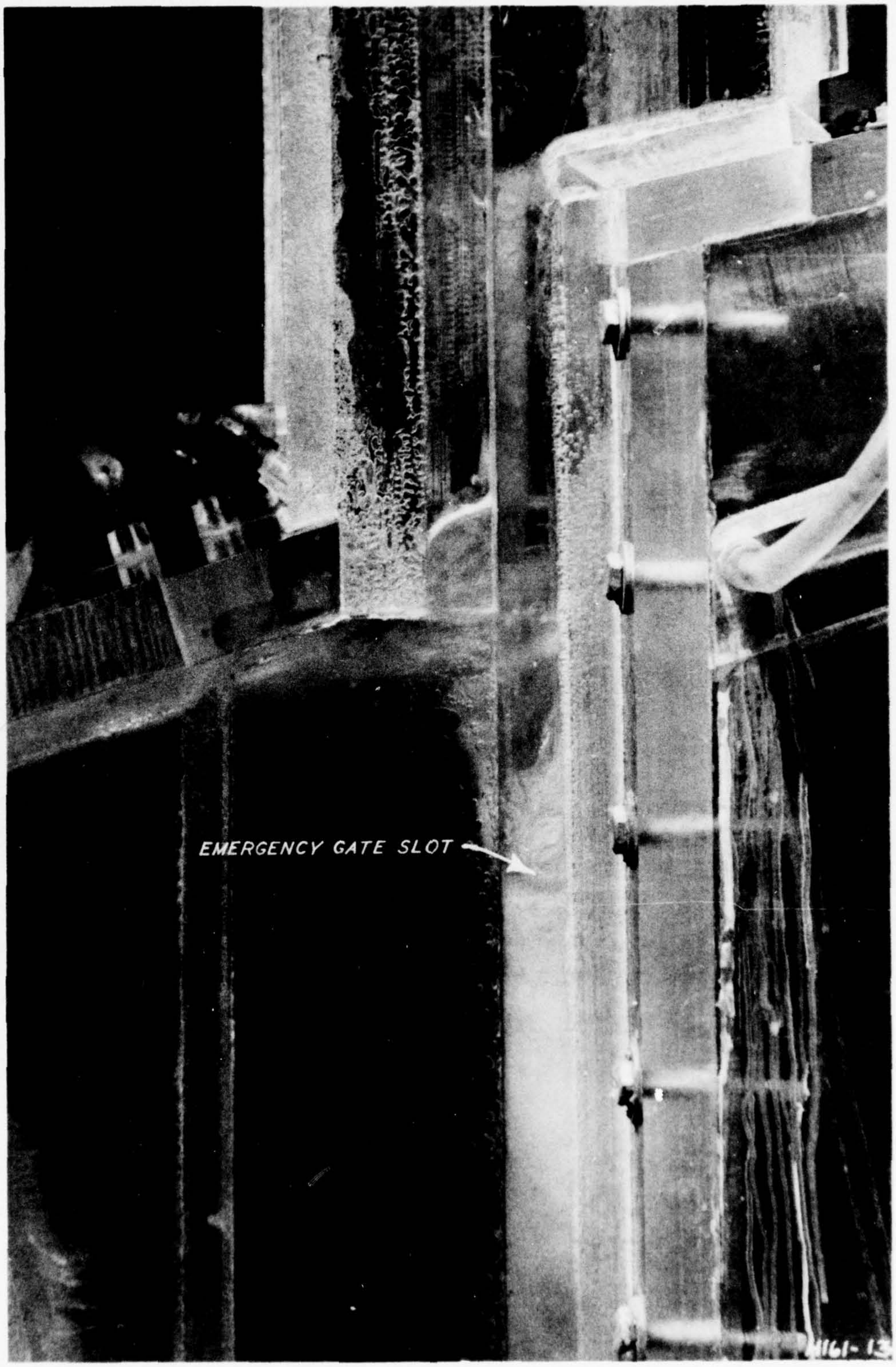
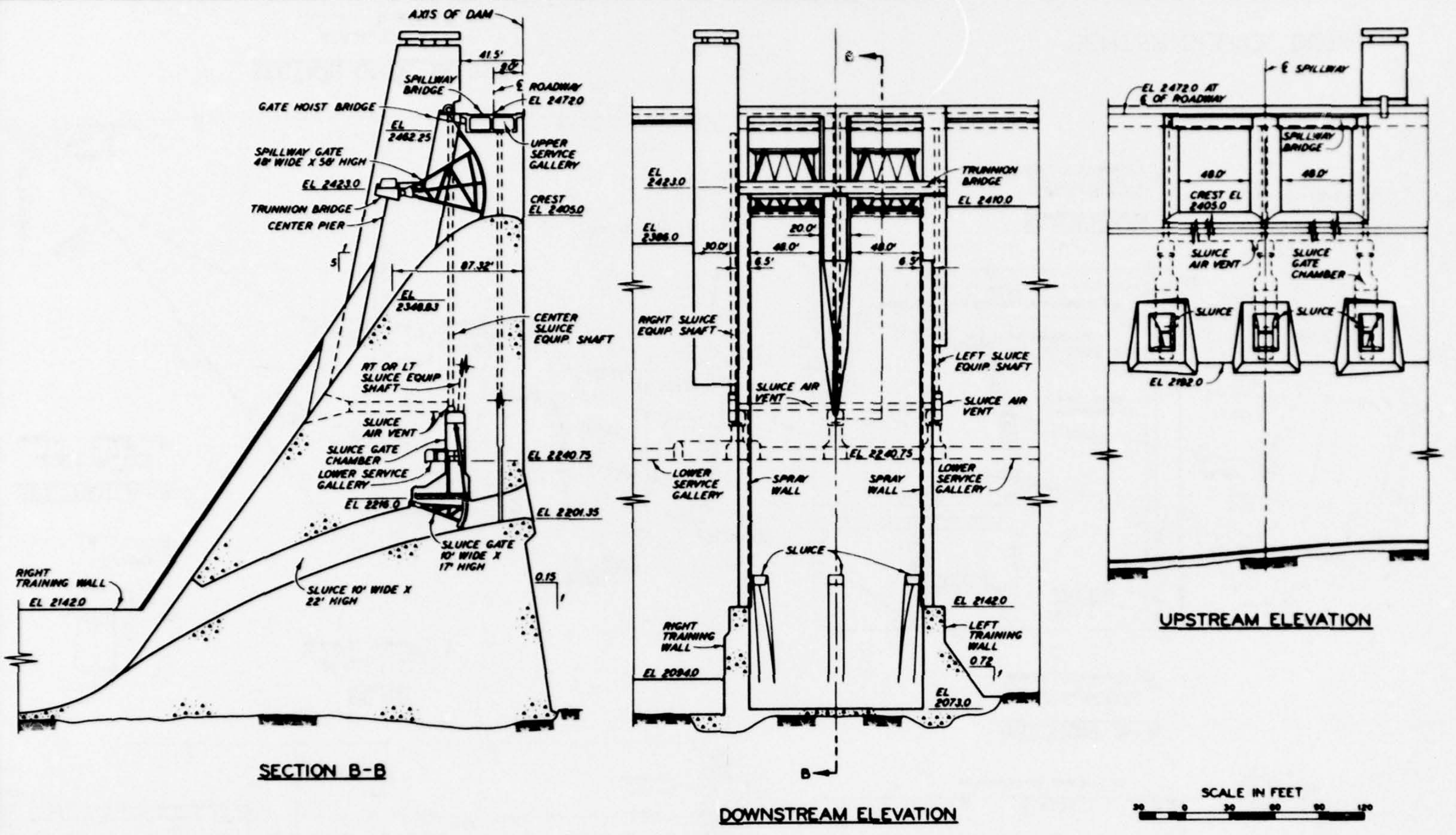
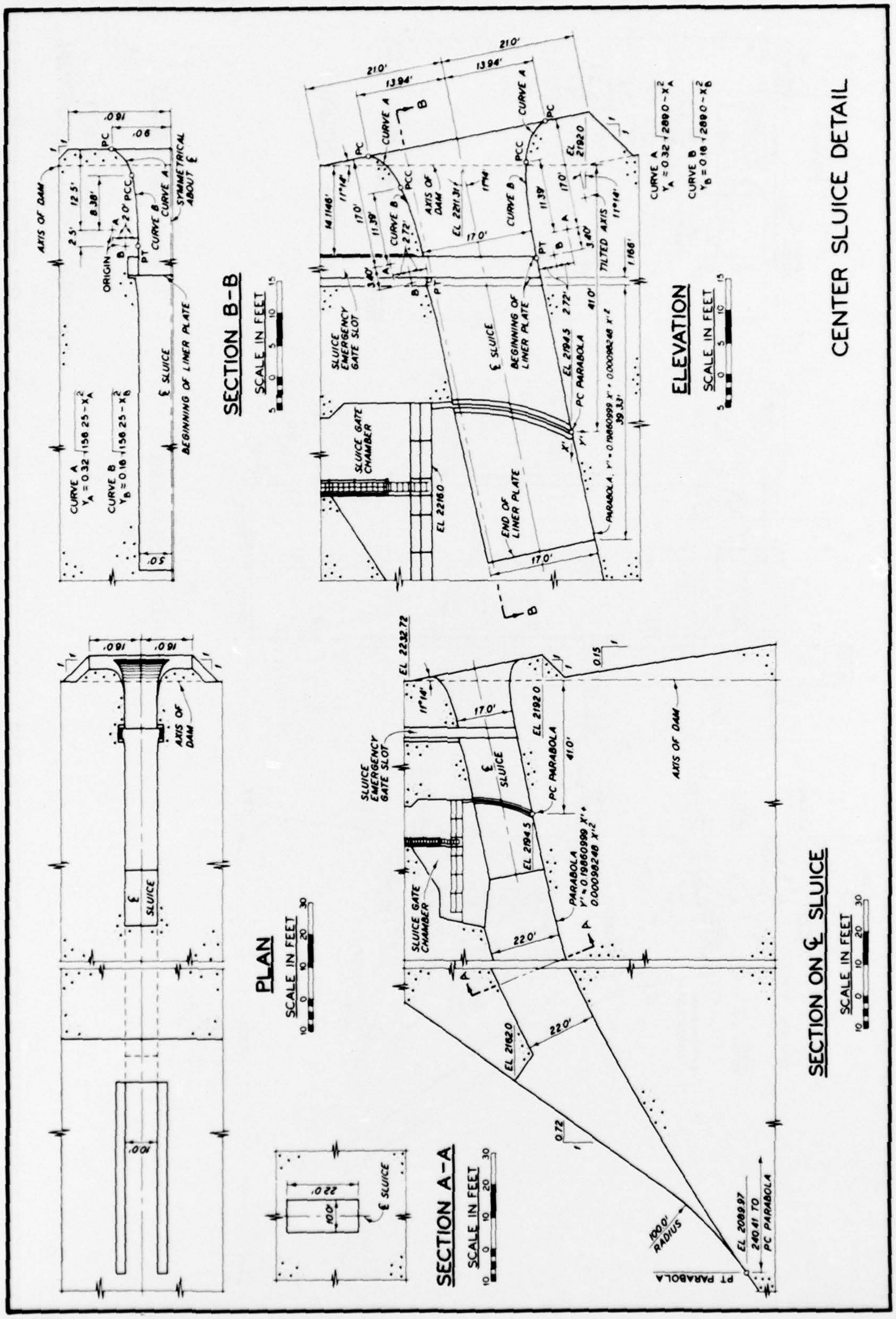



Photo 2. Flow impingement upon sidewall gate slot with roof modification

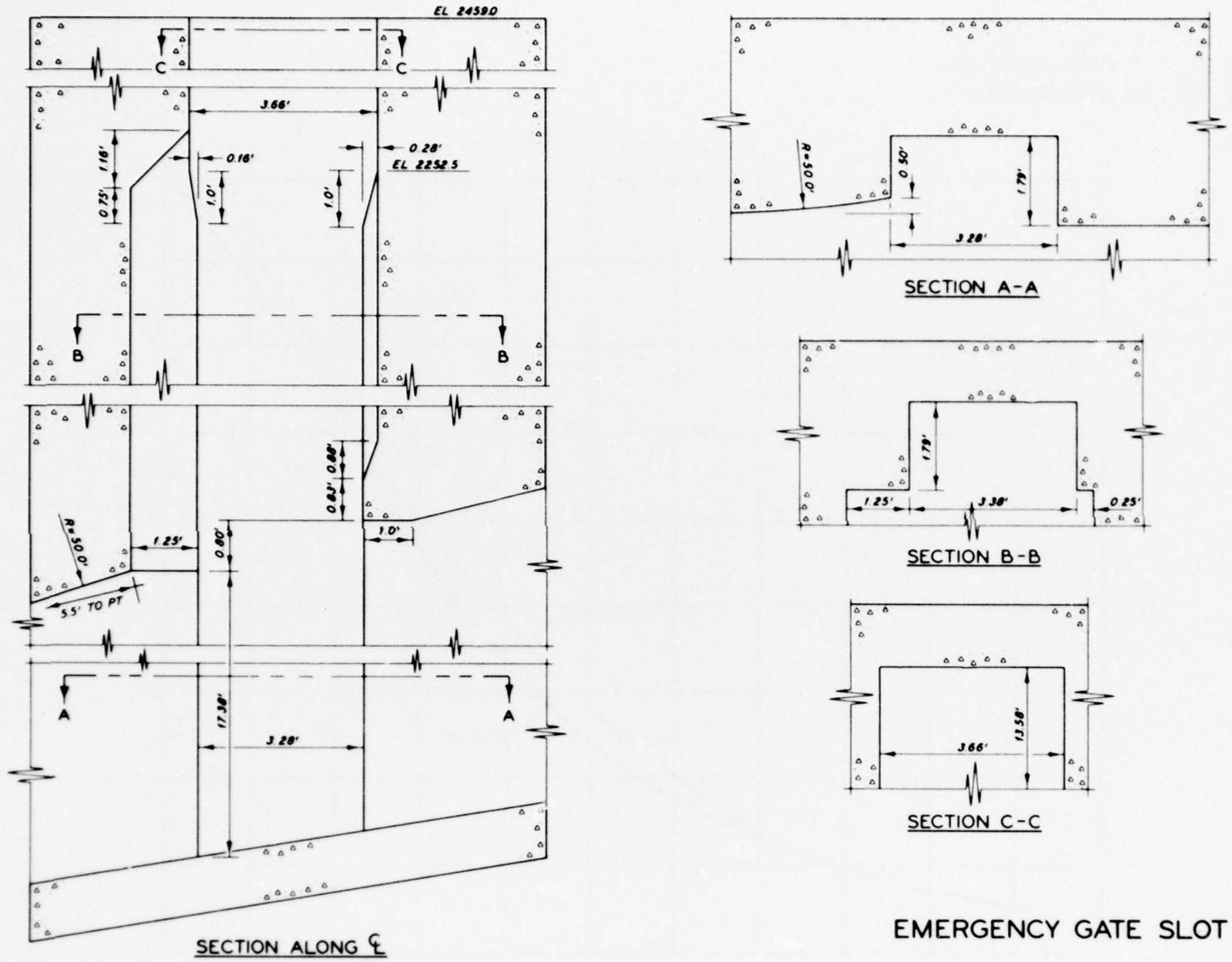



SPILLWAY AND
SLUICE CONFIGURATION

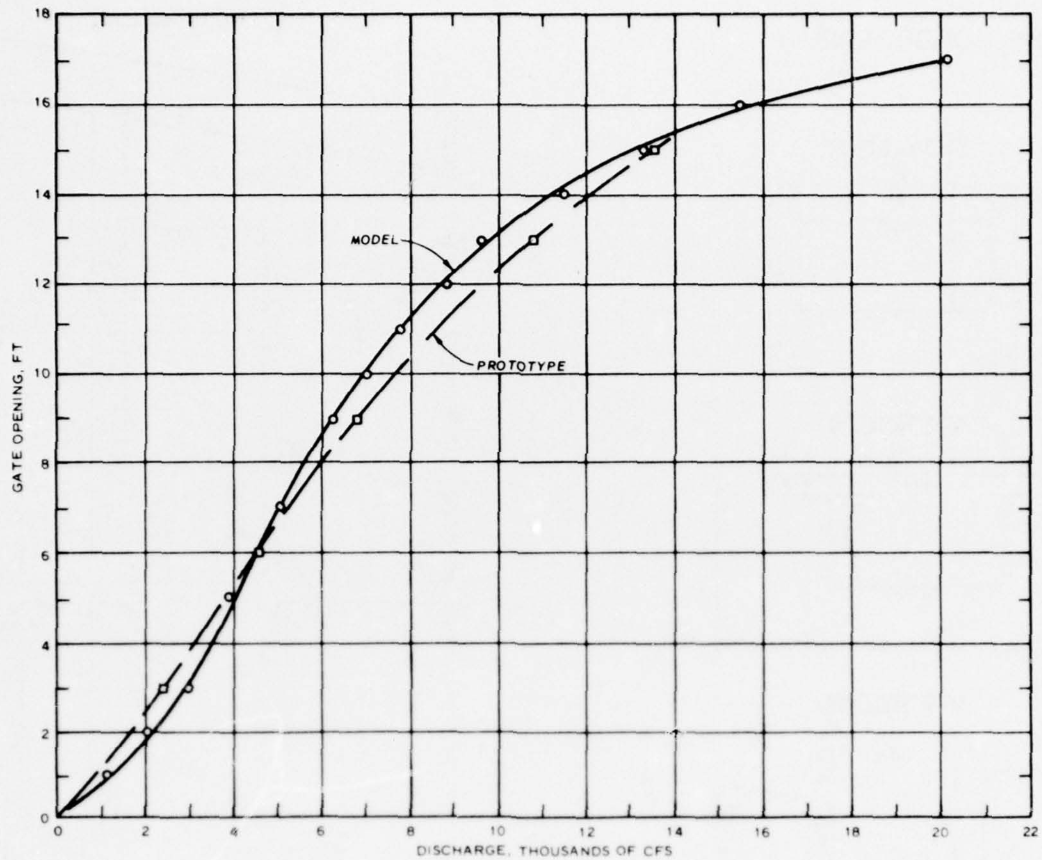


CENTER SLUICE DETAIL
PLAN
SCALE IN FEET
SECTION A-A
SCALE IN FEET
SECTION B-B
SCALE IN FEET
ELEVATION
SCALE IN FEET
SECTION ON ℄ SLUICE
SCALE IN FEET
CURVE A $Y_A = 0.32\sqrt{156.25 - X_A^2}$
CURVE B $Y_B = 0.18\sqrt{156.25 - X_B^2}$
CURVE A $Y_A = 0.32\sqrt{2890 - X_A^2}$
CURVE B $Y_B = 0.18\sqrt{2890 - X_B^2}$
AXIS OF DAM
SYMMETRICAL ABOUT ℄
BEGINNING OF LINER PLATE
END OF LINER PLATE
SLUICE EMERGENCY GATE SLOT
SLUICE GATE CHAMBER
TILTED AXIS
PC PARABOLA
PARABOLA $Y' = 0.19860999 X' + 0.00098248 X'^2$
EL 2192.0
EL 2194.5
EL 2198.0
EL 2211.31
EL 2232.72
EL 2162.0
EL 2089.97
240.41 TO PC PARABOLA
PT PARABOLA
100.0' RADIUS

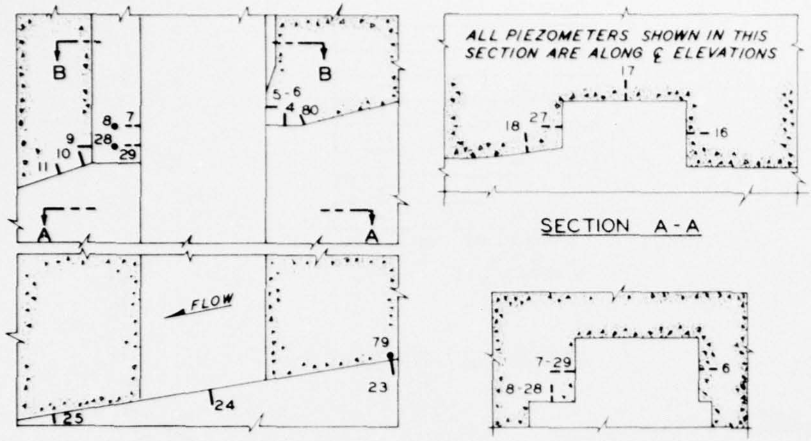

PLATE 2




EMERGENCY GATE SLOT DETAIL




**DISCHARGE RATING CURVE**
**FULL AND PARTIAL GATE OPENINGS**
POOL ELEV 2459



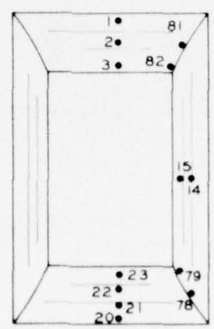

SECTION ALONG ℄ AT GATE SLOT

SECTION A-A

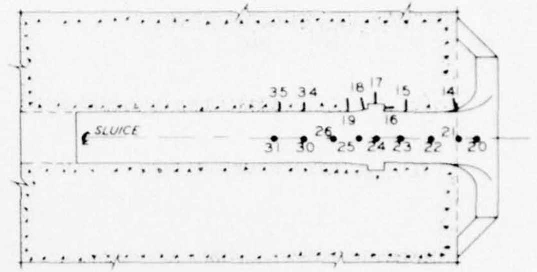
SECTION B-B

EMERGENCY GATE SLOT DETAIL

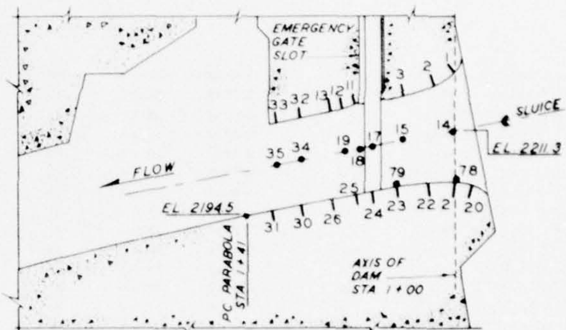
| PIEZ NO | PIEZ STA | PIEZ ELEV | PIEZ NO | PIEZ STA | PIEZ ELEV |
|---|---|---|---|---|---|
| 1 | 1+00 | 2223.0 | 21 | 0+98.7 | 2201.3 |
| 2 | 1+04 | 2220.5 | 22 | 1+05 | 2201.2 |
| 3 | 1+10 | 2218.3 | 23 | 1+11 | 2200.4 |
| 4 | 1+13.6 | 2217.4 | 24 | 1+15.8 | 2199.5 |
| 5 | 1+14.1 | 2217.9 | 25 | 1+19 | 2198.9 |
| 6 | 1+14.1 | 2217.9 | 26 | 1+24 | 2197.9 |
| 7 | 1+17.4 | 2217.6 | 27 | 1+17.4 | 2207.8 |
| 8 | 1+18 | 2217.6 | 28 | 1+18 | 2217.1 |
| 9 | 1+18.6 | 2216.9 | 29 | 1+17.4 | 2217.1 |
| 10 | 1+18.8 | 2216.5 | 30 | 1+30 | 2196.7 |
| 11 | 1+19.4 | 2216.3 | 31 | 1+36 | 2195.9 |
| 12 | 1+22 | 2215.0 | 32 | 1+30 | 2213.4 |
| 13 | 1+24 | 2214.6 | 33 | 1+35 | 2212.4 |
| 14 | 1+00 | 2211.3 | 34 | 1+30 | 2205.3 |
| 15 | 1+10 | 2209.3 | 35 | 1+35 | 2204.8 |
| 16 | 1+14.1 | 2208.5 | 78 | 0+98.7 | 2201.9 |
| 17 | 1+15.8 | 2208.2 | 79 | 1+11 | 2201.5 |
| 18 | 1+18.4 | 2207.6 | 80 | 1+13 | 2217.5 |
| 19 | 1+21.4 | 2207.0 | 81 | 1+04 | 2220.5 |
| 20 | 0+96 | 2200.7 | 82 | 1+10 | 2218.3 |



BELL-MOUTHED INTAKE

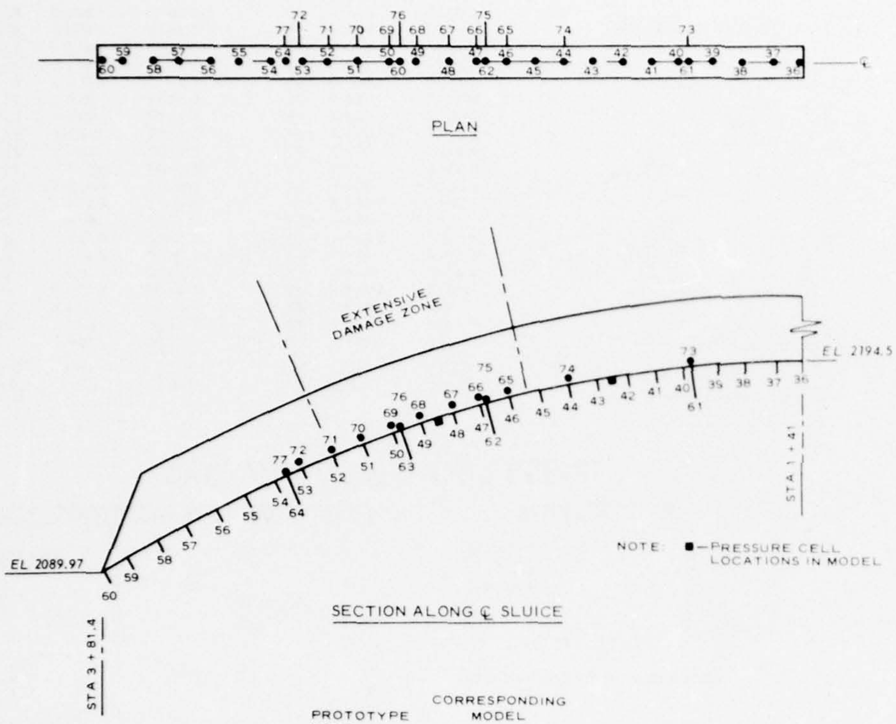



PLAN




SECTION ALONG ℄ SLUICE

# PIEZOMETER LOCATIONS
## UPSTREAM OF SLUICE GATE

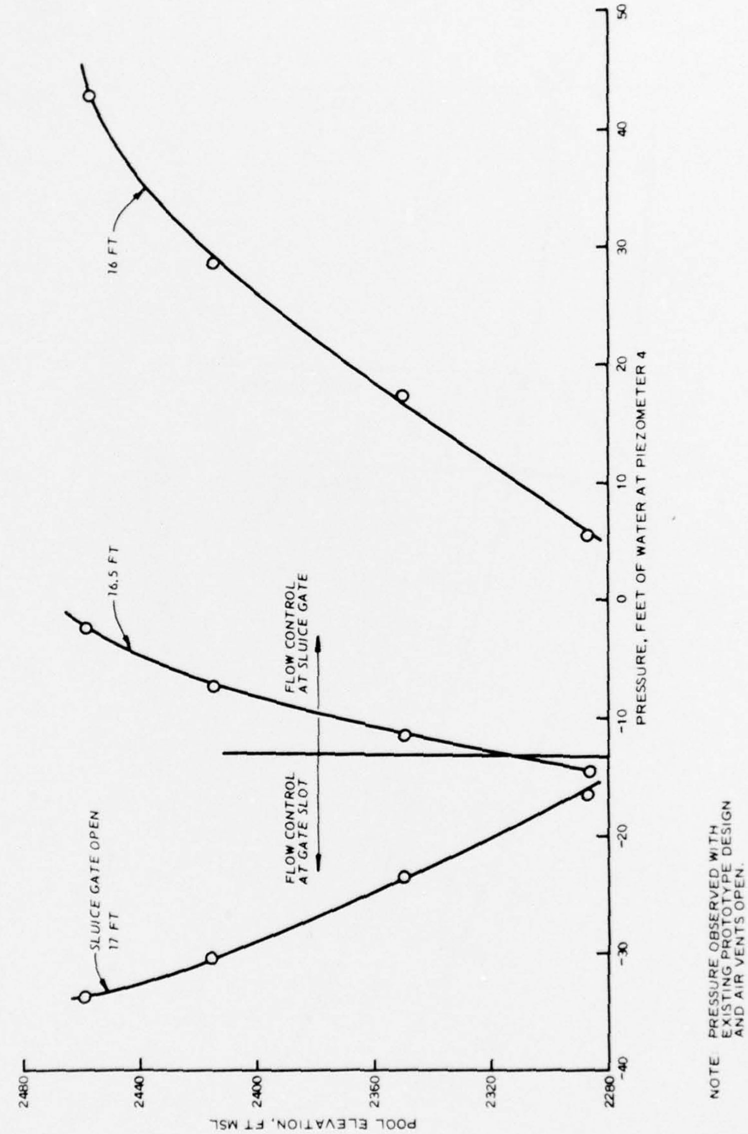



| PROTOTYPE PRESS, CELLS | CORRESPONDING MODEL PIEZOMETERS |
|---|---|
| 1 | 61 |
| 2 | 44 |
| 3 | 62 |
| 3A | 75 |
| 4 | 48 |
| 5 | 63 |
| 5A | 76 |
| 6 | 64 |

| PIEZ NO. | PIEZ STA | PIEZ ELEV | PIEZ NO. | PIEZ STA | PIEZ ELEV |
|---|---|---|---|---|---|
| 36 | 1 + 42 | 2194.3 | 57 | 3 + 51 | 2109.5 |
| 37 | 1 + 51 | 2192.8 | 58 | 3 + 61 | 2103.3 |
| 38 | 1 + 61 | 2190.4 | 59 | 3 + 71 | 2097.1 |
| 39 | 1 + 71 | 2187.7 | 60 | 3 + 80 | 2090.9 |
| 40 | 1 + 81 | 2185.0 | 61 | 1 + 78.4 | 2184.2 |
| 41 | 1 + 91 | 2182.1 | 62 | 2 + 49.6 | 2161.3 |
| 42 | 2 + 01 | 2179.0 | 63 | 2 + 77.2 | 2149.2 |
| 43 | 2 + 11 | 2175.8 | 64 | 3 + 15.4 | 2130.0 |
| 44 | 2 + 21 | 2172.3 | 65 | 2 + 41 | 2167.1 |
| 45 | 2 + 31 | 2168.7 | 66 | 2 + 51 | 2163.1 |
| 46 | 2 + 41 | 2164.8 | 67 | 2 + 61 | 2158.9 |
| 47 | 2 + 51 | 2160.8 | 68 | 2 + 71 | 2154.9 |
| 48 | 2 + 61 | 2156.8 | 69 | 2 + 81 | 2149.7 |
| 49 | 2 + 71 | 2152.1 | 70 | 2 + 91 | 2145.0 |
| 50 | 2 + 81 | 2147.4 | 71 | 3 + 01 | 2139.6 |
| 51 | 2 + 91 | 2142.9 | 72 | 3 + 11 | 2134.9 |
| 52 | 3 + 01 | 2137.6 | 73 | 1 + 78.4 | 2186.0 |
| 53 | 3 + 11 | 2132.6 | 74 | 2 + 21 | 2172.6 |
| 54 | 3 + 21 | 2126.9 | 75 | 2 + 49.6 | 2161.6 |
| 55 | 3 + 31 | 2121.3 | 76 | 2 + 77.2 | 2149.5 |
| 56 | 3 + 41 | 2115.5 | 77 | 3 + 15.4 | 2130.3 |

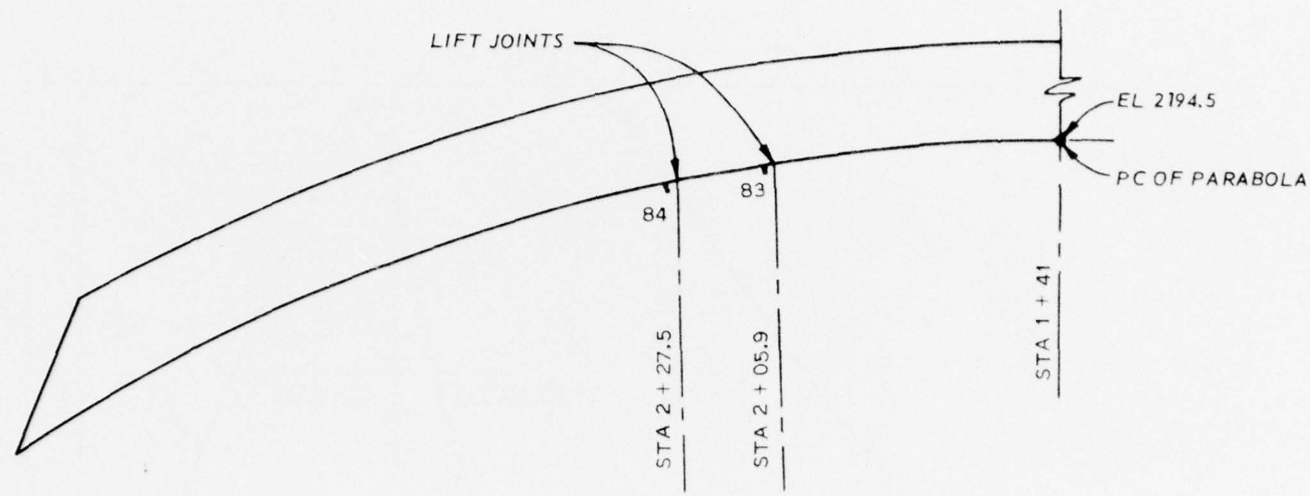
PIEZOMETER LOCATIONS
DOWNSTREAM OF SLUICE GATE

## MINIMUM PRESSURES IN SLUICE INTAKE



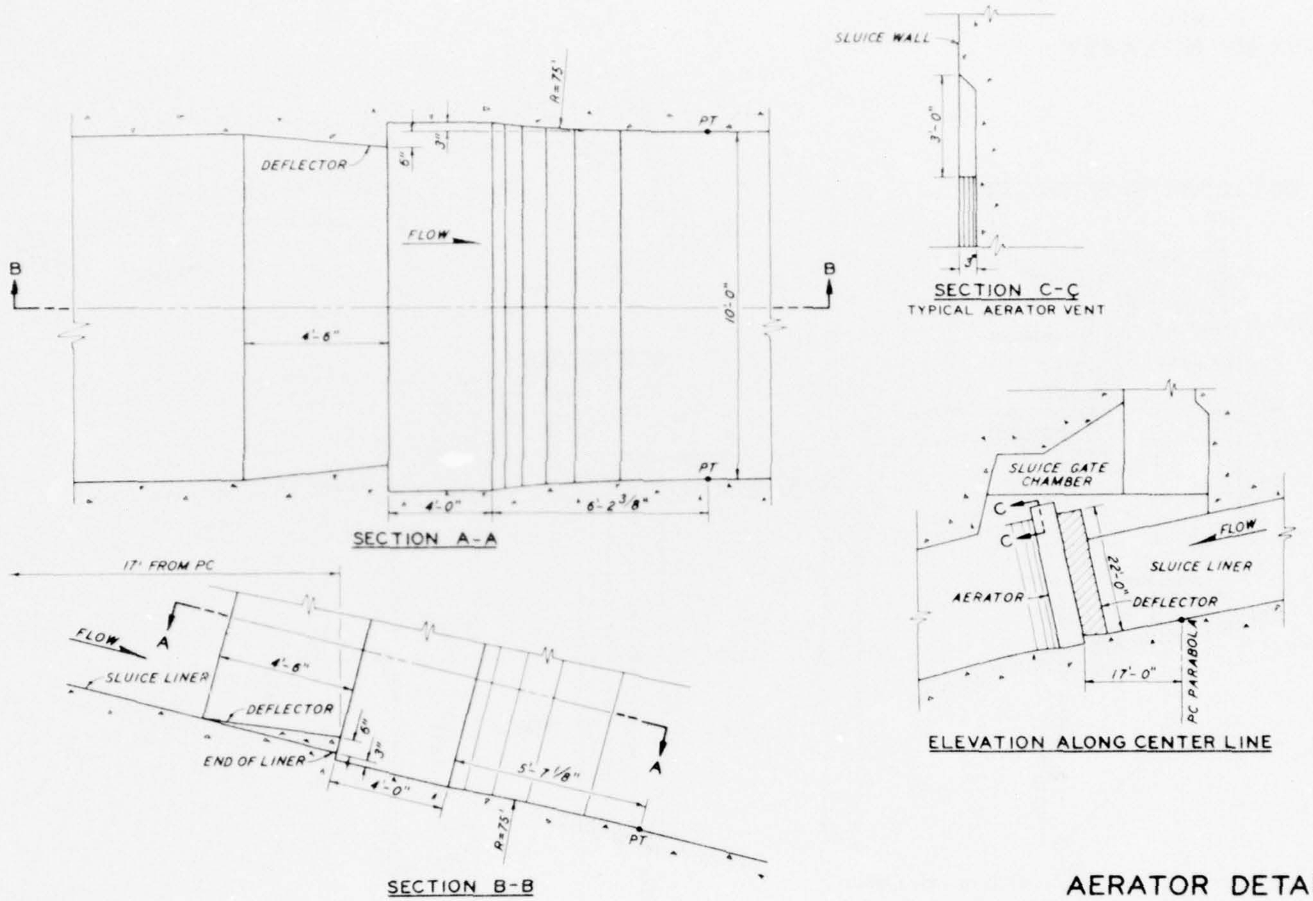

NOTE: PRESSURE OBSERVED WITH EXISTING PROTOTYPE DESIGN AND AIR VENTS OPEN.

| PIEZOMETER | STA | EL |
|---|---|---|
| 83 | 2 + 06.4 | 2177.4 |
| 84 | 2 + 28.0 | 2169.9 |

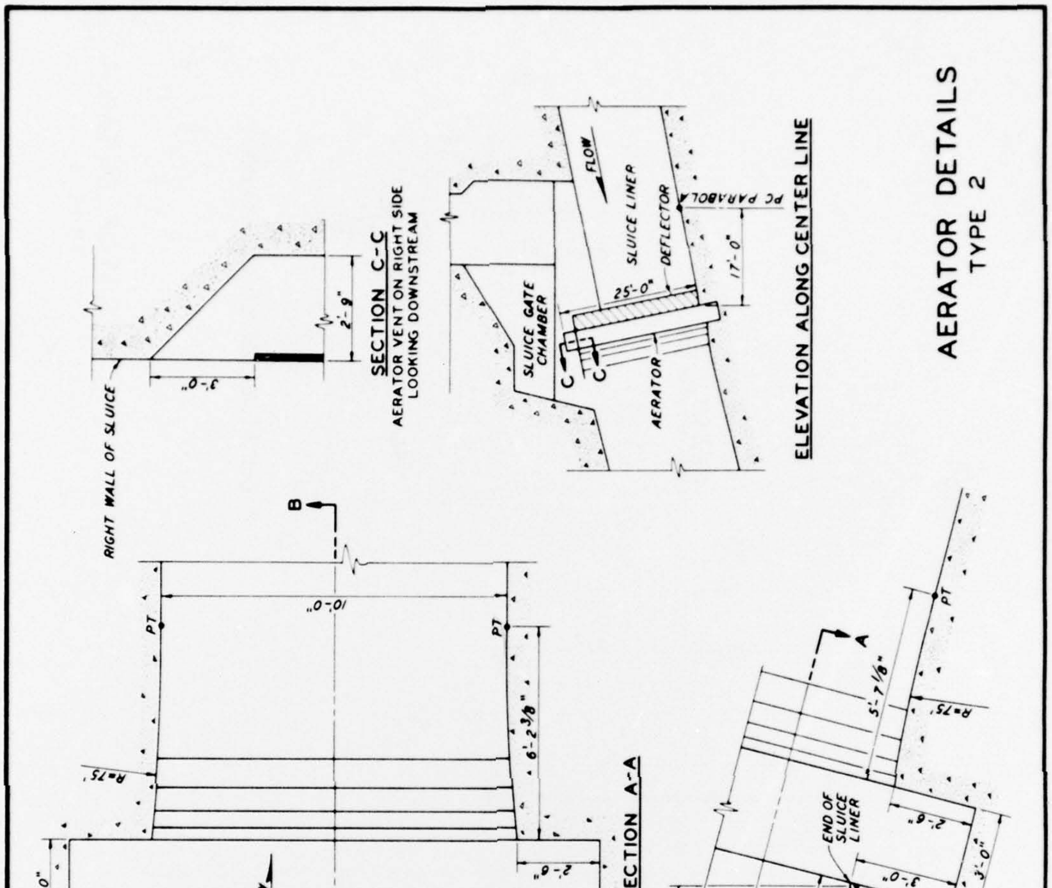


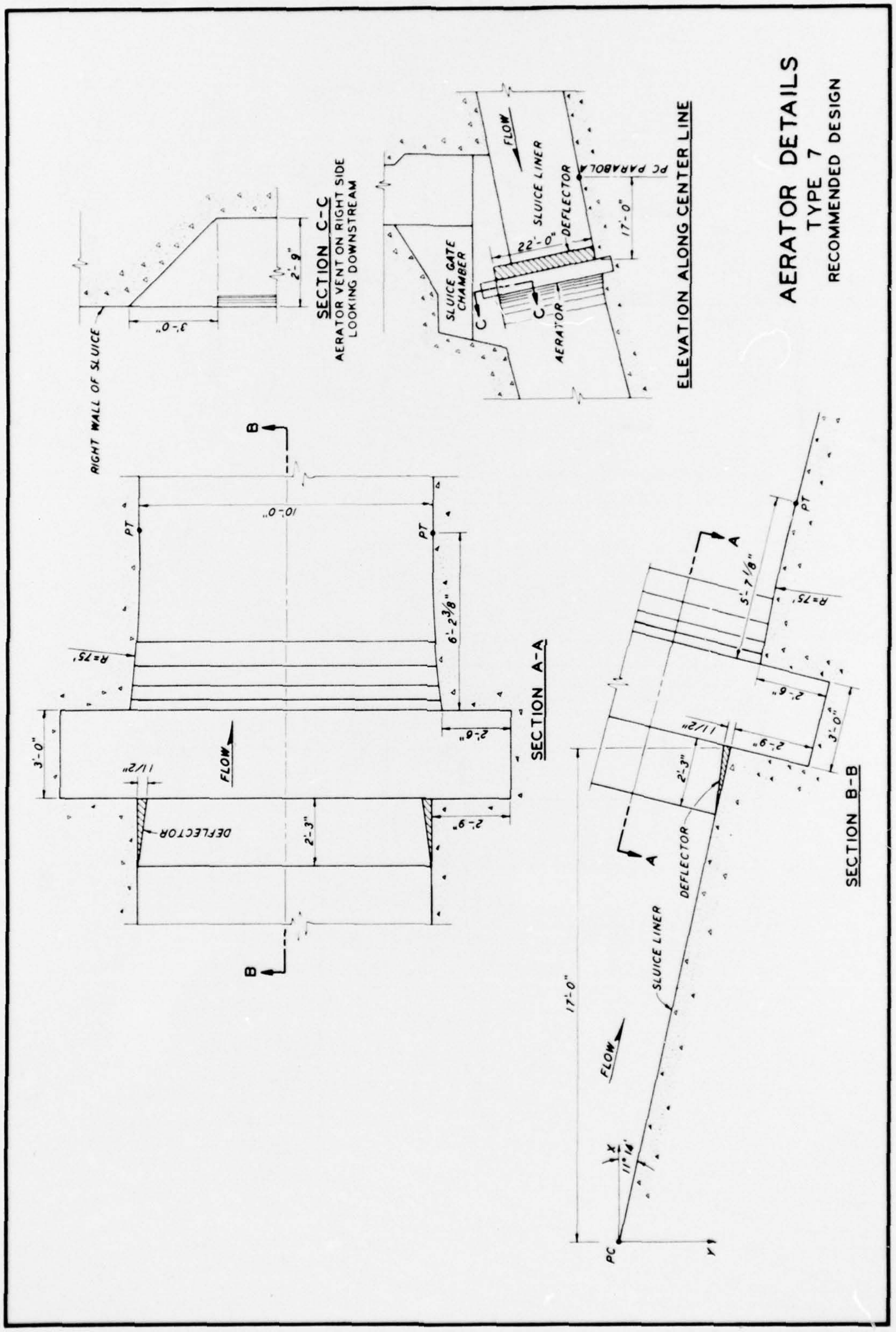

SECTION ALONG ℄ SLUICE

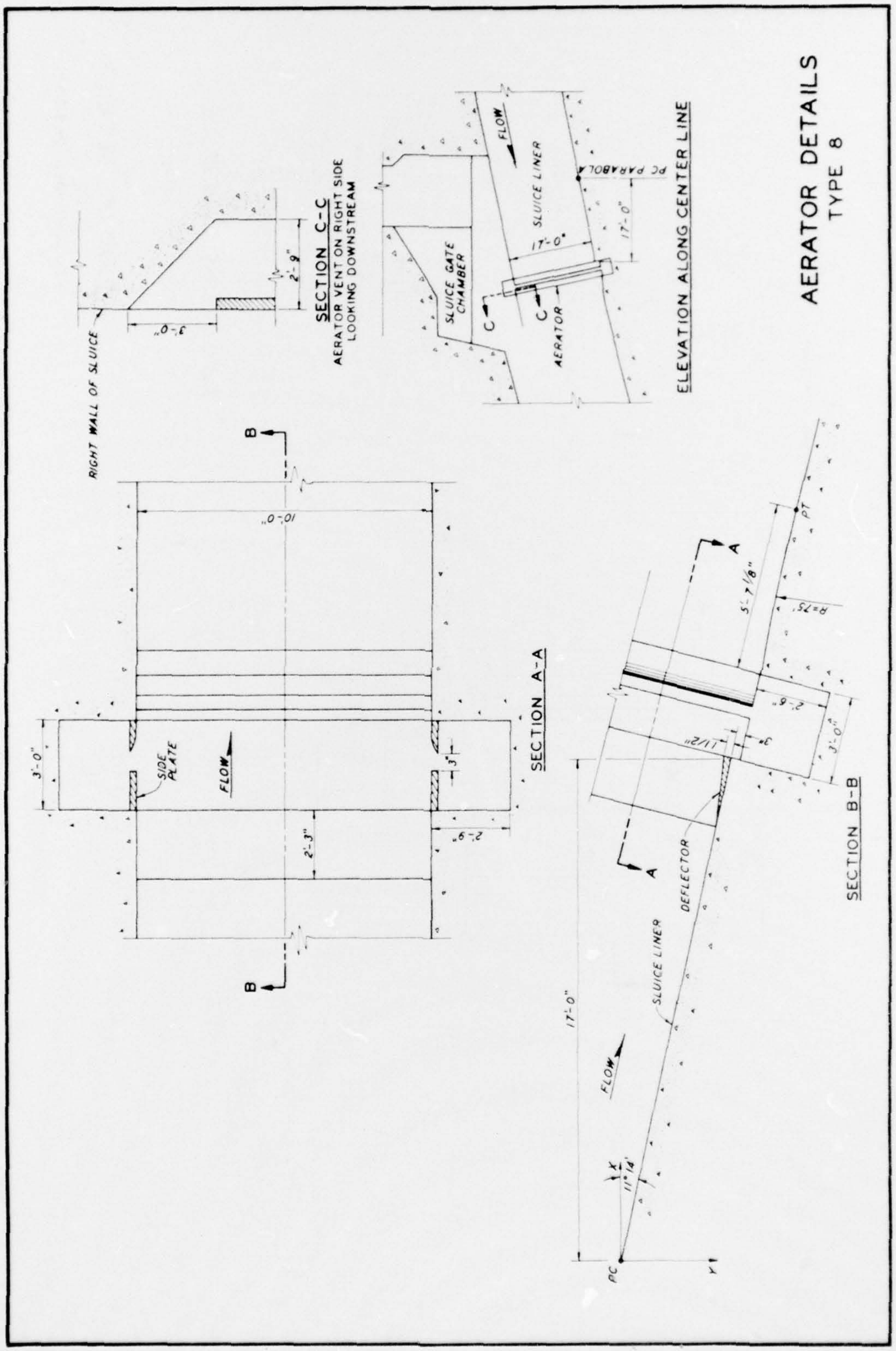
LIFT JOINT LOCATION
REPRODUCED IN MODEL SLUICE

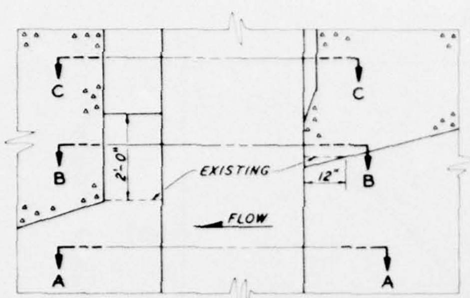



AERATOR DETAILS
TYPE 1

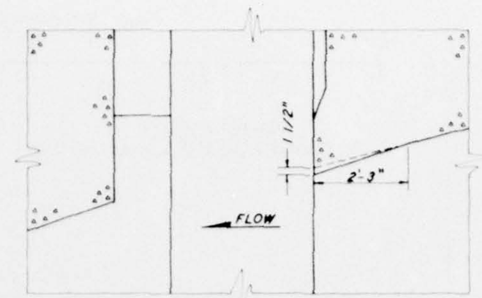

AERATOR DETAILS
TYPE 2
SECTION A-A
SECTION B-B
SECTION C-C
AERATOR VENT ON RIGHT SIDE
LOOKING DOWNSTREAM
ELEVATION ALONG CENTER LINE
RIGHT WALL OF SLUICE
3" DEFLECTOR CONSTANT U/S SIDE
DEFLECTOR
FLOW
SLUICE LINER
END OF SLUICE LINER
3" LIFT AT INVERT
SLUICE GATE CHAMBER
AERATOR
PC PARABOLA
PT
PC
R=75'
10'-0"
6'-2 3/8"
5'-7 1/8"
3'-0"
2'-6"
2'-3"
2'-9"
17'-0"
25'-0"
11°14'
A
B
C


AERATOR DETAILS
TYPE 7
RECOMMENDED DESIGN
SECTION A-A
SECTION B-B
SECTION C-C
AERATOR VENT ON RIGHT SIDE
LOOKING DOWNSTREAM
ELEVATION ALONG CENTER LINE
RIGHT WALL OF SLUICE
SLUICE GATE CHAMBER
SLUICE LINER
DEFLECTOR
AERATOR
FLOW
PC PARABOLA
PC
PT
R=75'
10'-0"
6'-2 3/8"
3'-0"
2'-9"
2'-3"
2'-6"
1 1/2"
5'-7 1/8"
17'-0"
22'-0"
11° 14'


AERATOR DETAILS
TYPE 8
SECTION C-C
AERATOR VENT ON RIGHT SIDE
LOOKING DOWNSTREAM
RIGHT WALL OF SLUICE
3'-0"
2'-9"
ELEVATION ALONG CENTER LINE
FLOW
SLUICE LINER
SLUICE GATE CHAMBER
AERATOR
PC PARABOLA
17'-0"
SECTION A-A
SIDE PLATE
10'-0"
3'-0"
2'-3"
2'-9"
3"
SECTION B-B
DEFLECTOR
11°14'
5'-7 1/8"
R=75'
2'-6"
3'-0"
1 1/2"
PT
PC

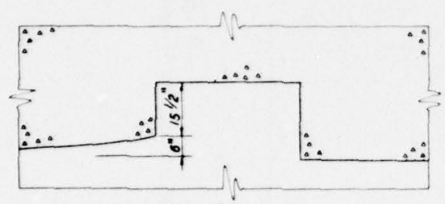



MODIFICATION 1 (RECOMMENDED)

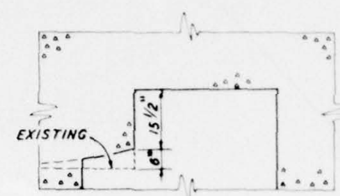



MODIFICATION 2

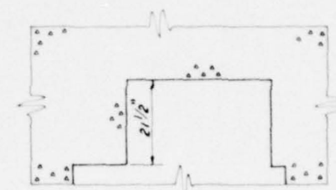
ELEVATIONS ALONG CENTER LINE OF EMERGENCY GATE SLOT




SECTION A-A

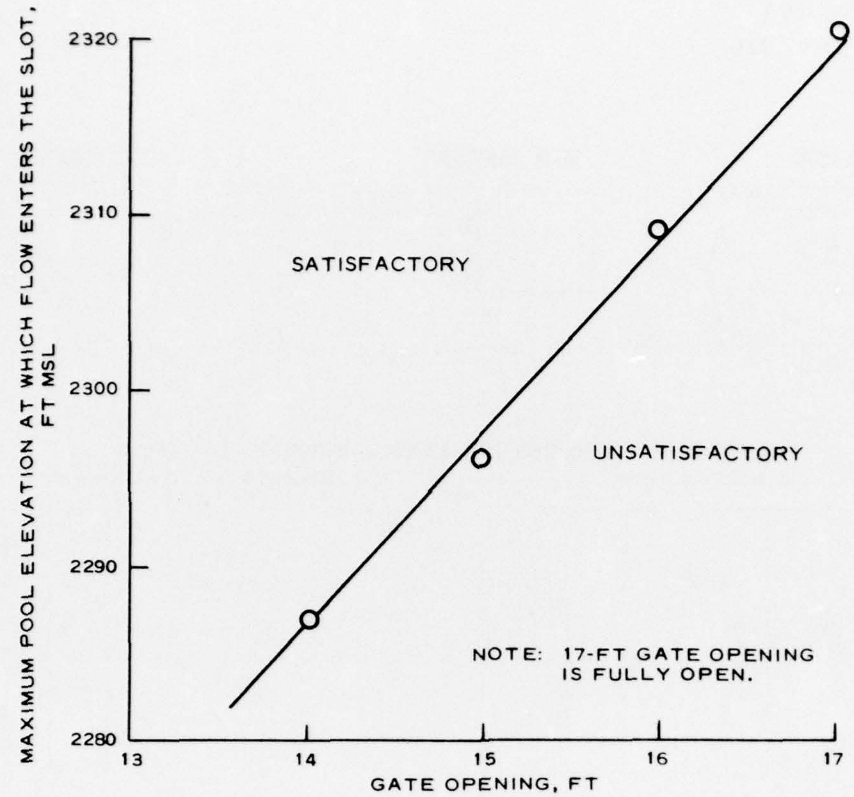



SECTION B-B




SECTION C-C

INTAKE MODIFICATIONS AT
EMERGENCY GATE SLOT




MINIMUM OPERATING CONDITIONS
TYPE 7 AERATOR

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Dortch, Mark S
Center sluice investigation, Libby Dam, Kootenai River, Montana; hydraulic model investigation, by Mark S. Dortch. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report H-76-21)
Prepared for U. S. Army Engineer District, Seattle, Seattle, Washington.

1. Hydraulic models. 2. Kootenai River. 3. Libby Dam. 4. Sluices (Hydraulic engineering). I. U. S. Army Engineer District, Seattle. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report H-76-21)
TA7.W34 no.H-76-21